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The Quality of Our Nation's Waters

Water Quality in the Mississippi Embayment–Texas Coastal Uplands Aquifer System and Mississippi River Valley Alluvial Aquifer, South-Central United States, 1994–2008

National Water-Quality Assessment Program

Circular 1356

U.S. Department of the Interior
U.S. Geological Survey

Cover. Yazoo River, Humphreys County, Mississippi. Photograph by Jim Wark, Airphoto North America.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

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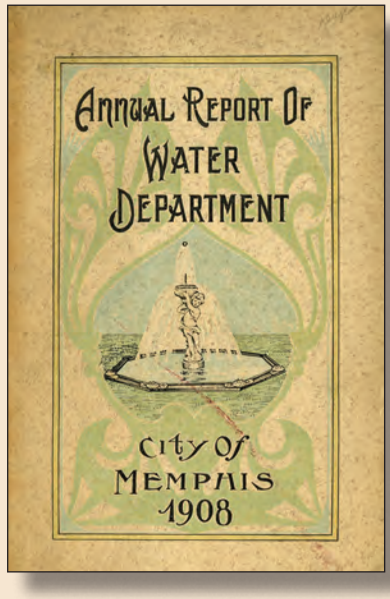
NAWQA

National Water-Quality Assessment Program

A letter from “The Artesian Water Supply at Memphis,” 1887, Memphis Tennessee Water Department, describing the quality of groundwater in one of the first artesian wells in the City of Memphis. The samples from the 354-foot deep Bohlen-Huse Ice Company well were sent to Dr. Charles Smart of the U.S. Army for analysis.

> *Both samples were clear, colorless, transparent and without odor, having soft, pleasant taste, even at the temperature of 80 degrees Fahr., when the experiment was made. They contained a small quantity of pulverulent, rusty sediment, which under the microscope was found to consist of exceedingly minute particles of sand with darker particles of iron. No organic debris was discovered, and only a trace of infusorial life.*
>
> *This water is somewhat similar in its character to that of a rain water which has been shed from a clean roof and has undergone the natural purifying process which takes place during storage in a sound, clean, underground cistern, and as such is fit for all domestic and economic purposes. There are, however, few cistern waters, perhaps none, that are as pure as this water. Its freedom from organic matter is such that I have rarely met with natural water which gives less response to the tests for organic matter.*
>
> *I know of no city which has a water supply as pure as the samples now reported on.*
>
> *Dated at Washington D.C., this eighteenth day of June, 1887.*
>
> *Charles Smart,*
> *Major and Surgeon U.S. Army*



Photograph from Sorrels[32]

Foreword

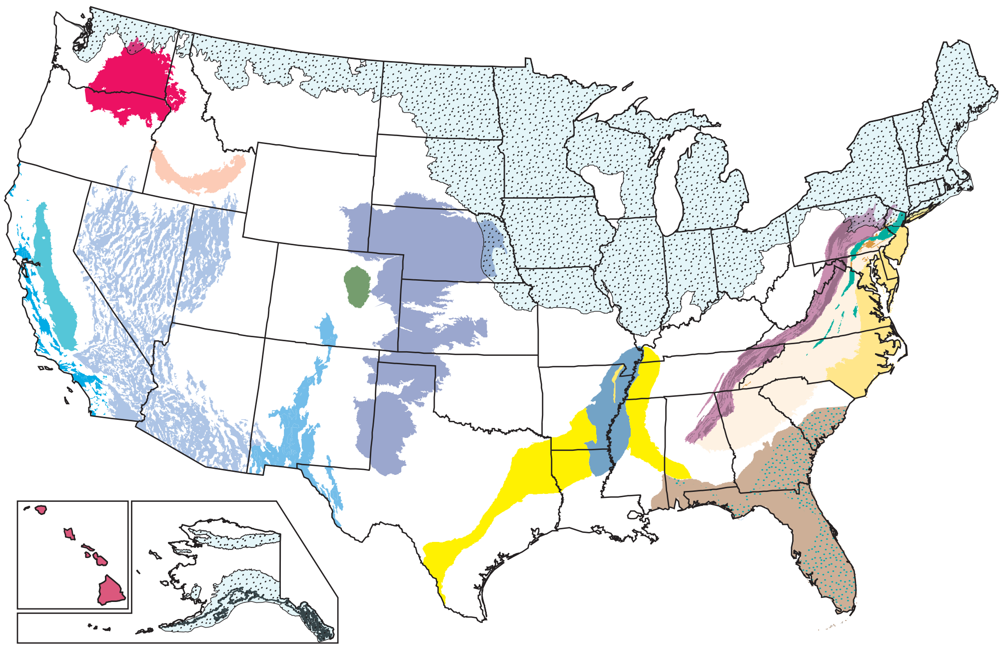
The United States has made major investments in assessing, managing, regulating, and conserving natural resources, such as water and a variety of ecosystems. Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of millions of people (*http://water.usgs.gov/nawqa/applications/*).

Two decades ago, Congress established the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program to meet this need. Since then NAWQA has served as a primary source of nationally consistent information on the quality of the Nation's streams and groundwater, on ways in which water quality changes over time, and on the natural features and human activities affecting the quality of streams and groundwater. Objective and reliable data, systematic scientific studies, and models are used to characterize where, when, and why the Nation's water quality is degraded—and what can be done to improve and protect the water for human and ecosystem needs. This information is critical to our future because the Nation faces an increasingly complex and growing need for clean water to support people, economic growth, and healthy ecosystems. For example, NAWQA findings for public-supply wells, which provide water to about 105 million people, showed that 22 percent of source-water samples contained at least one contaminant at levels of potential health concern. Similarly, 23 percent of samples from domestic (or privately owned) wells, which supply untreated water to an additional 43 million people, also had contaminant levels of potential concern.

This report is one of a collection of publications that describe water-quality conditions in selected Principal Aquifers of the United States (*http://water.usgs.gov/nawqa/studies/praq/*). The collection is part of the series "The Quality of Our Nation's Waters," which describes major findings of the NAWQA Program on water-quality issues of regional and national concern and which provides science-based information for assessing and managing the quality of our groundwater resources. Other reports in this series focus on occurrence and distribution of nutrients, pesticides, and volatile organic compounds in streams and groundwater, the effects of contaminants and streamflow alteration on the condition of aquatic communities in streams, and the quality of untreated water from private domestic and public-supply wells. Each report builds toward a more comprehensive understanding of the quality of regional and national water resources (*http://water.usgs.gov/nawqa/nawqa_sumr.html*). All NAWQA reports are available online at *http://water.usgs.gov/nawqa/bib/*.

The information in this series primarily is intended for those interested or involved in resource management and protection, conservation, regulation, and policymaking at regional and national levels. In addition, the information should be of interest to those at a local level who wish to know more about the general quality of streams and groundwater in areas near where they live and how that quality compares with other areas across the Nation. We hope this publication will provide you with insights and information to meet your needs and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

Jerad Bales
Acting Associate Director for Water
U.S. Geological Survey



Principal Aquifers and Water-Quality Summary Reports

National summary of groundwater quality in Principal Aquifers—Circular 1360

High Plains aquifer system—Circular 1337

Glacial aquifer system—Circular 1352

Northern Atlantic Coastal Plain surficial aquifer system—Circular 1353

Piedmont, Blue Ridge, and Valley and Ridge aquifers—Circular 1354

- Piedmont and Blue Ridge carbonate-rock aquifers
- Piedmont and Blue Ridge crystalline-rock aquifers
- Valley and Ridge siliciclastic-rock aquifers
- Valley and Ridge carbonate-rock aquifers
- Early Mesozoic basin aquifers

Upper Floridan aquifer and overlying surficial aquifers—Circular 1355

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- Mississippi River Valley alluvial aquifer

Denver Basin aquifer system—Circular 1357

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Contents

Introduction to This Report

This report contains the major findings of a regional assessment of water quality in the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer in the south-central United States. It is one of a series of reports by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program that present major findings for Principal Aquifers, other aquifers, and major river basins across the Nation. In these reports, water quality is discussed in terms of local, State, regional, and national issues. Conditions in these aquifers are compared to conditions found elsewhere and to selected national benchmarks, such as those for drinking-water quality.

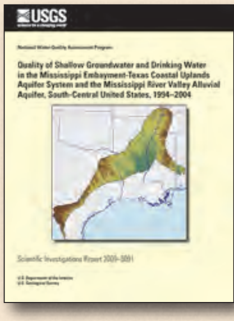
This report is intended for individuals working with water-resource issues in local, State, or Federal agencies, universities, public interest groups, or the private sector. The information will be useful in addressing current issues, such as drinking-water quality, source-water protection, and monitoring and sampling strategies. This report also will be useful for individuals who wish to know more about the quality of groundwater in areas near where they live and how that quality of water compares to the quality of water in other areas across the region and the Nation.

Water-quality conditions in the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer summarized in this report are discussed in greater detail in other reports listed in the references. Detailed technical information, data and analyses, sample collection and analytical methodology, models, graphs, and maps that support the findings presented in this report in addition to reports in this series from other Principal Aquifers can be accessed from the national NAWQA Web site (*http://water.usgs.gov/nawqa/*).

"USGS NAWQA studies and research of groundwater quality and the connection to surface-water quality are changing our understanding of how the natural water system of the Mississippi embayment functions. The region must find better ways to manage our water and USGS research is absolutely essential to that goal."

Dean Pennington
Executive Director of the Yazoo Mississippi Delta Joint Water Management District

Companion studies of these aquifers are discussed in the following reports.

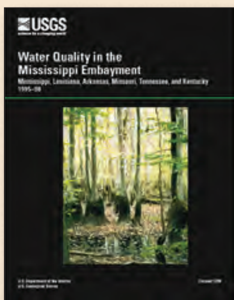


Quality of shallow groundwater and drinking water in the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer, south-central United States, 1994–2004

U.S. Geological Survey Scientific Investigations Report 2009–5091

By Heather L. Welch, James A. Kingsbury, Roland W. Tollett, and Ronald C. Seanor

(Also available at *http://pubs.usgs.gov/sir/2009/5091/*)



Water quality in the Mississippi Embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98

U.S. Geological Survey Circular 1208

By Barbara A. Kleiss, Richard H. Coupe, Gerard J. Gonthier, and Billy G. Justus

(Also available at *http://pubs.usgs.gov/circ/circ1208/*)

Quality of shallow ground water in recently developed residential and commercial areas, Memphis vicinity, Tennessee, 1997

U.S. Geological Survey Water-Resources Investigations Report 02–4294

By Gerard J. Gonthier

(Also available at *http://pubs.er.usgs.gov/publication/wri024294/*)

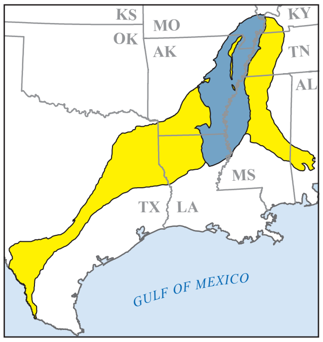
Chapter 1: *Overview of Major Findings and Implications*

Of the nearly 10 million people that live in areas overlying the Mississippi embayment–Texas coastal uplands aquifer system, about 80 percent rely on groundwater from this aquifer system for their drinking water. This aquifer system is the primary source of drinking water for more than a million people in the Memphis, Tennessee, area.

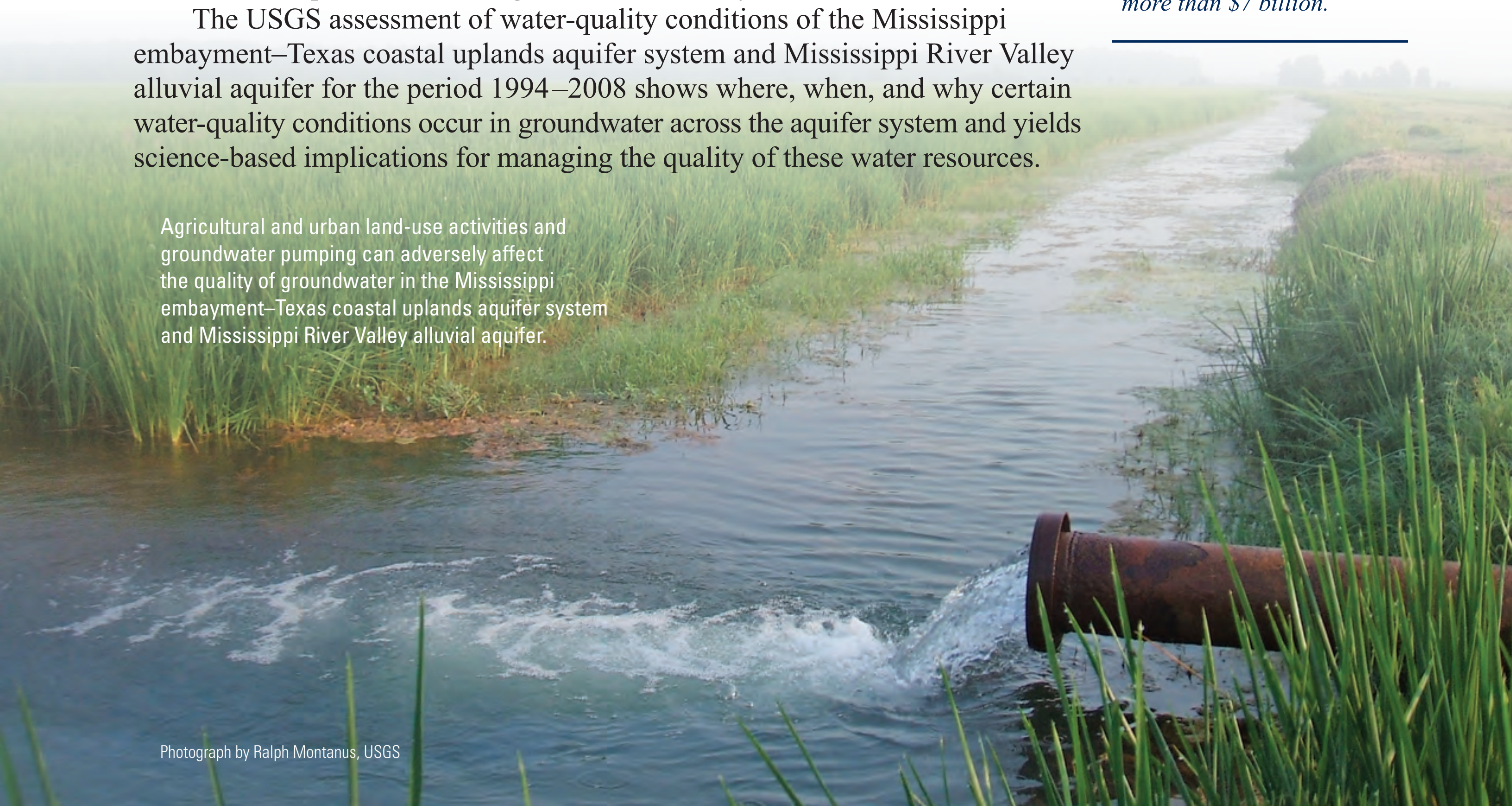
The overlying Mississippi River Valley alluvial aquifer provides drinking water for domestic use and small communities in rural areas, but its primary importance to the region is as a source of water for irrigation. Irrigation withdrawals from this aquifer are the third largest in the Nation and play a key role in the economy of the area, where annual crop sales total more than $7 billion.

The long-term management and sustainability of this vital resource is critical. Water levels are declining in these aquifers where large amounts of pumping occur, which has adversely affected groundwater quality in some areas. The quality of groundwater in these aquifers has implications for human health, for rural agricultural economies, and for the costs associated with land and water management, conservation, and regulation. Understanding the natural and human factors that control groundwater quality in these aquifers is an essential step toward ensuring their sustainability.

The USGS assessment of water-quality conditions of the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer for the period 1994–2008 shows where, when, and why certain water-quality conditions occur in groundwater across the aquifer system and yields science-based implications for managing the quality of these water resources.



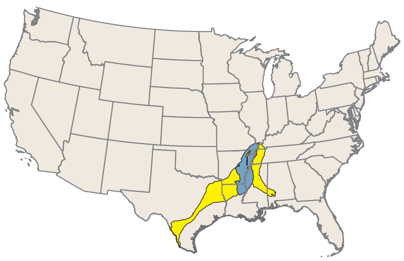
The amount of groundwater pumped from the Mississippi River Valley alluvial aquifer for irrigation ranks third in the Nation and plays a key role in the economy of the area, where annual crop sales total more than $7 billion.



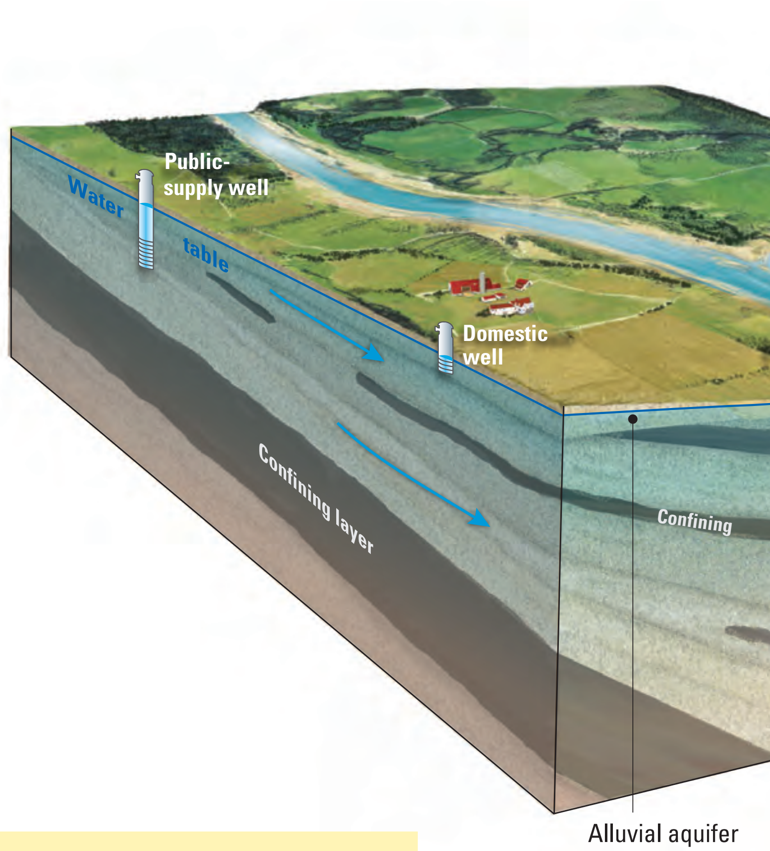
Agricultural and urban land-use activities and groundwater pumping can adversely affect the quality of groundwater in the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer.

Photograph by Ralph Montanus, USGS

Overview of Major Findings and Implications for the Mississippi Mississippi River Valley Alluvial Aquifer



About 8 million people rely on groundwater from the Mississippi embayment–Texas coastal uplands aquifer system for drinking water. The Mississippi River Valley alluvial aquifer also provides drinking water for domestic use in rural areas but is of primary importance to the region as a source of water for irrigation. Irrigation withdrawals from this aquifer are among the largest in the Nation and play a key role in the economy of the area, where annual crop sales total more than $7 billion. The reliance of the region on both aquifers for drinking water and irrigation highlights the importance of long-term management to sustain the availability and quality of these resources.



1 Few contaminants were detected at concentrations greater than human-health benchmarks

Contaminants derived from geologic sources were measured at elevated concentrations more commonly than manmade contaminants such as pesticides. Radon, manganese, and arsenic were measured at concentrations of potential human-health concern in about 30, 10, and 3 percent of samples, respectively, from aquifers used as sources of drinking water. See pages 25–30 and 48–50.

2 Groundwater is a source of phosphorus to streams in the lower Mississippi River watershed

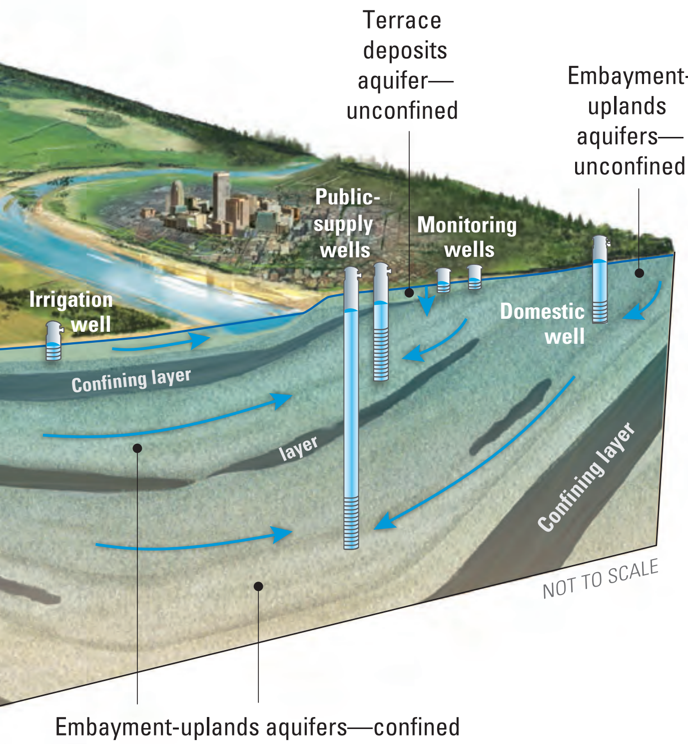
The median concentration of dissolved phosphorus (0.6 milligram per liter) in the Mississippi River Valley alluvial aquifer is more than 10 times greater than is typical for groundwater. Elevated concentrations of phosphorus in streams can lead to excessive algal growth, decreased oxygen levels, and fish kills. During dry conditions, groundwater seepage into the streambed makes up most of the flow in streams. Understanding of the role of groundwater as a source of phosphorus to streams is an important consideration in the ongoing development of State nutrient management strategies. See pages 38–40.

Embayment–Texas Coastal Uplands Aquifer System and

3 Nitrate concentrations in shallow groundwater were low despite widespread fertilizer use

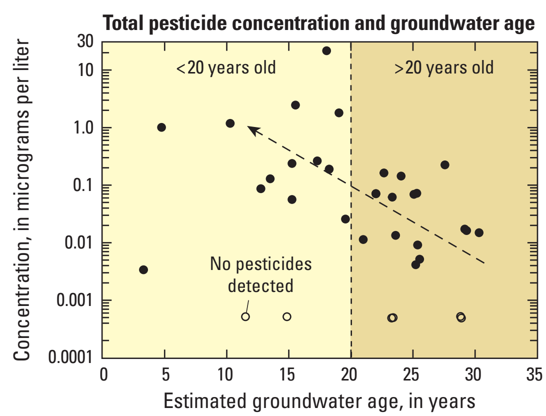
Although agriculture is the predominant land use in the Mississippi River Valley, nitrate was detected infrequently in shallow groundwater in the alluvial aquifer. Where nitrate was detected, concentrations were low (usually less than 1 milligram per liter) in large part because of the anoxic conditions throughout most of the aquifer that result in the natural removal of nitrate by denitrification. See pages 41–44.

Photograph by Lynn Betts, USDA NRCS



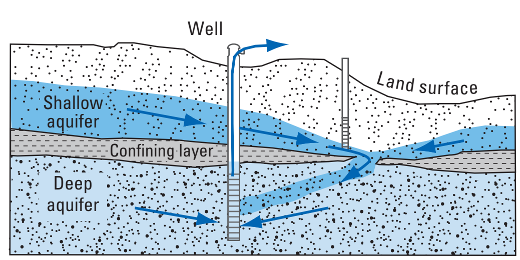
4 Groundwater is most vulnerable to contamination where groundwater residence times are short

One or more pesticides or volatile organic compounds were detected in samples from 42 percent of shallow wells. For example, these contaminants were detected most commonly and at the highest concentrations in the Memphis, Tennessee, area where sources of these contaminants are located and where oxic groundwater was less than 20 years old. See pages 45–46.



5 Vulnerability of deep aquifers may increase in areas of high-volume pumping

Groundwater pumping of the Mississippi embayment–Texas coastal uplands aquifer system has lowered water levels by as much as 300 feet, increasing the potential for contaminants to be transported to the deep aquifers used for drinking water. Pesticides and volatile organic compounds detected in shallow groundwater in the Memphis area could move downward into the deeper aquifer that supplies water to more than 1 million people. See page 52.



Photographs from top to bottom: Bill Cobb, used with permission; Alan M. Cressler, USGS; Alan M. Cressler, USGS; USGS

Overview of Major Findings *Water-Coastal Uplands Aquifer System and Mississippi River*

1 Few contaminants were detected at concentrations greater than human-health benchmarks.

Samples collected from 242 wells in the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer were analyzed for 285 constituents. Only nine contaminants were detected at a concentration greater than a human-health benchmark, and only two of these contaminants (radon and manganese) exceeded a benchmark in more than 10 percent of samples. Contaminants, such as radon, manganese, and arsenic, that are derived from geologic sources were measured at concentrations greater than human-health benchmarks more commonly than were manmade organic contaminants. Only one manmade contaminant, the insecticide dieldrin, was measured at a concentration greater than the human-health benchmark. The occurrence of dieldrin primarily in shallow groundwater in an urban area likely is the result of its past use as a termiticide.

In rural areas, domestic wells are the primary source of drinking water for more than 1 million people. Unlike public-supply wells, the quality and safety of water from domestic wells are not regulated by the Federal Safe Drinking Water Act. The widespread detection of contaminants with geologic sources in domestic wells emphasizes the need for public education aimed at describing where these contaminants are likely to occur and what testing and treatment options are available.

2 Groundwater is a source of phosphorus to streams in the lower Mississippi River watershed.

Groundwater typically is not considered an important source of phosphorus to streams because phosphorus tends to bind to soils and aquifer materials and, as a result, is not transported in groundwater. Concentrations of dissolved phosphorus in the Mississippi River Valley alluvial aquifer, however, were among the highest measured in groundwater across the Nation. Aquifer sediments are the primary source of phosphorus in groundwater.

Groundwater discharge and irrigation return flow make up most of the flow in streams overlying the Mississippi River Valley alluvial aquifer during low-flow conditions. The estimated contribution of dissolved phosphorus from groundwater was about 8 percent of the annual total instream load for one stream overlying the Mississippi River Valley alluvial aquifer. During late summer and early fall, when streamflow is low, the phosphorus contribution from groundwater can be as much as 25 percent. The role of groundwater as a source of phosphorus to streams will be an important consideration in the ongoing development of State nutrient management strategies, as well as strategies to reduce the size of the hypoxic zone in the Gulf of Mexico.

Quality Issues for the Mississippi Embayment–Texas Valley Alluvial Aquifer, South-Central United States

3 Nitrate concentrations in shallow groundwater were low despite widespread fertilizer use.

Despite the large amounts of nitrogen-containing fertilizers applied to fields overlying the Mississippi River Valley alluvial aquifer, concentrations of nitrate in the shallow groundwater in this aquifer were low. Concentrations of nitrate generally were less than 0.1 milligram per liter (mg/L) as nitrogen (N), which is 10 times less than the 1 mg/L as N threshold commonly used to indicate inputs from human-related sources and far below the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level of 10 mg/L as N. Fine-grained sediments limit recharge to the aquifer. Low recharge rates, combined with organic-rich soils and aquifer sediments, create low dissolved-oxygen conditions that enable bacteria to reduce the nitrate in groundwater to nitrogen gas. This natural attenuation process limits the transport of nitrate in the aquifer.

4 Groundwater is most vulnerable to contamination where groundwater residence times are short.

Shallow groundwater in the Mississippi embayment–Texas coastal uplands aquifer system and Mississippi River Valley alluvial aquifer is vulnerable to contamination from activities at land surface, as indicated by the occurrence of one or more pesticides or volatile organic compounds (VOCs) in samples from 42 percent of shallow wells. These manmade contaminants were detected most commonly and at the highest concentrations where groundwater residence times were short (groundwater less than 20 years old) and the groundwater was oxic (containing dissolved oxygen). Data characterizing shallow groundwater quality are useful for providing early warnings of potential water-quality problems that might be difficult to remediate, as well as helping to prioritize where monitoring the water of deep, drinking-water aquifers might be most cost effective.

Photographs from top to bottom: Alan M. Cressler, USGS; Lynn Betts, USDA NRCS; USGS; USGS

5 Vulnerability of deep aquifers may increase in areas of high-volume pumping.

Groundwater pumping of the Mississippi embayment–Texas coastal uplands aquifer system has lowered water levels by as much as 300 feet (ft). Water levels in the middle Claiborne aquifer have declined as much as 70 ft to meet the water needs of about 1 million people living in and near Memphis, Tennessee. Changes in water levels associated with prolonged high volume pumping affect groundwater flow within and between aquifers and increase the potential for contaminants to be transported to the deep aquifers used for drinking water. Pesticides and VOCs that were frequently detected in the shallow aquifer system have the potential to leak into the deeper aquifer in areas where the confining layer is thin or absent. In southern Arkansas and north-central Louisiana, groundwater pumping for public supply and industrial uses has lowered water levels as much as 300 ft, causing naturally occurring saltwater to move into areas where the aquifer is used. As the demand for groundwater for irrigation and public supply in the region increases, sustainability of the aquifer system will depend on understanding how and if water quality changes in response to water-level declines.

Photograph by Alan M. Cressler, USGS

Chapter 2: *NAWQA Approach to Assessing Groundwater Quality*

Groundwater studies conducted as part of the USGS NAWQA Program in the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer were designed to answer broad questions about the occurrence, fate, and transport of contaminants in aquifers used as sources of drinking water.

This chapter summarizes the study design used to investigate water quality in the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer.

Water from domestic, public-supply, and irrigation wells and from monitoring wells in an urban area was sampled to characterize the quality of water in the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer.

Assessing the Water Quality in the Mississippi Embayment–Texas Coastal Uplands Aquifer System and the Mississippi River Valley Alluvial Aquifer

How does one go about characterizing the groundwater over an area as large as that covered by the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer, let alone the whole United States? The approach taken by the USGS is to use different types of groundwater studies to gain a better understanding of how and why water quality varies. These groundwater studies are the building blocks of the water-quality assessments of Principal Aquifers. Many studies were conducted in each Principal Aquifer, each with a different focus on information needs about groundwater quality and the natural and human-related factors that influence the aquifer (appendix 1). Groundwater studies were designed to answer the following questions: How does land use affect groundwater quality? How does water quality change as it moves through the aquifer? and What is the quality of the drinking-water resource? Groundwater studies designed to broadly assess water-quality conditions in aquifers used for drinking-water supply focused on sampling existing water-supply wells—these studies are called major aquifer studies. Agricultural and urban land-use studies designed to characterize and explain the quality of recently recharged groundwater (generally less than 10 years old)[1] in these land-use settings focused on mostly shallow monitoring (nonpumping) wells that were installed as part of the NAWQA Program. Other studies focused on public water supplies or groundwater quality along individual flow paths.[2, 3]

This Principal Aquifer assessment brings together and interprets results from all of the NAWQA groundwater studies in the Mississippi embayment–Texas coastal uplands aquifer system and the Mississippi River Valley alluvial aquifer (hereafter, the embayment-uplands aquifers and the alluvial aquifer). Throughout this assessment, the results are grouped into those that characterize the quality of groundwater used as a drinking-water supply and those that characterize the quality of groundwater that has recently been recharged in an urban land-use setting. The deep groundwater used for drinking-water supplies recharged the aquifer many years ago, in some cases long before any manmade chemicals were used on the land surface. The results of the land-use studies allow us to evaluate how our activities and the chemicals we use affect groundwater quality and can provide an early warning for potential contamination of drinking-water resources.

To assess the water-quality conditions of the groundwater used as a drinking-water resource, one sample was analyzed from each of about 210 randomly selected existing supply wells (see sidebar, NAWQA assessments use a wide range of geochemical data and site information, p. 14, and appendix 1). About 60 percent of the wells sampled were drinking-water wells; of these about half were domestic wells and half were public-supply wells (fig. 2–1). The other 40 percent were mostly irrigation wells but also included aquaculture, industrial, commercial, and livestock wells. The wells are distributed across much of the area overlying the aquifers, but, because the wells are located only in NAWQA groundwater study areas, some parts of the embayment-uplands aquifers, particularly in Mississippi and Alabama, are not represented (fig. 2–2). The wells sampled ranged in depth from very shallow (21 ft) to quite deep (nearly 1,500 ft) (table 2–1).

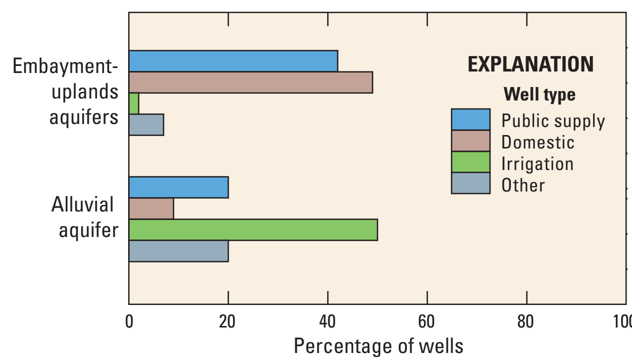


Figure 2–1. Most of the wells sampled in the embayment-uplands aquifers were drinking-water (domestic or public-supply) wells, and most of the wells sampled in the alluvial aquifer were irrigation wells.

Table 2–1. About half of the wells sampled were less than 200 ft deep and included a variety of well types and overlying land uses. Wells deeper than 200 ft were predominantly drinking-water wells.

Aquifer	Predominant land use	Number of wells sampled	Predominant well types	Well depth range, in feet
Shallow				
Alluvial aquifer	Agriculture	54	Irrigation	25–200
Embayment-uplands aquifers	Mixed land use	42	Domestic	21–200
Terrace deposits and embayment aquifers	Urban—residential and commercial	33	Monitoring	33–109
Deep				
Embayment-uplands aquifers	Mixed land use	110	Public supply and domestic	202–1,466

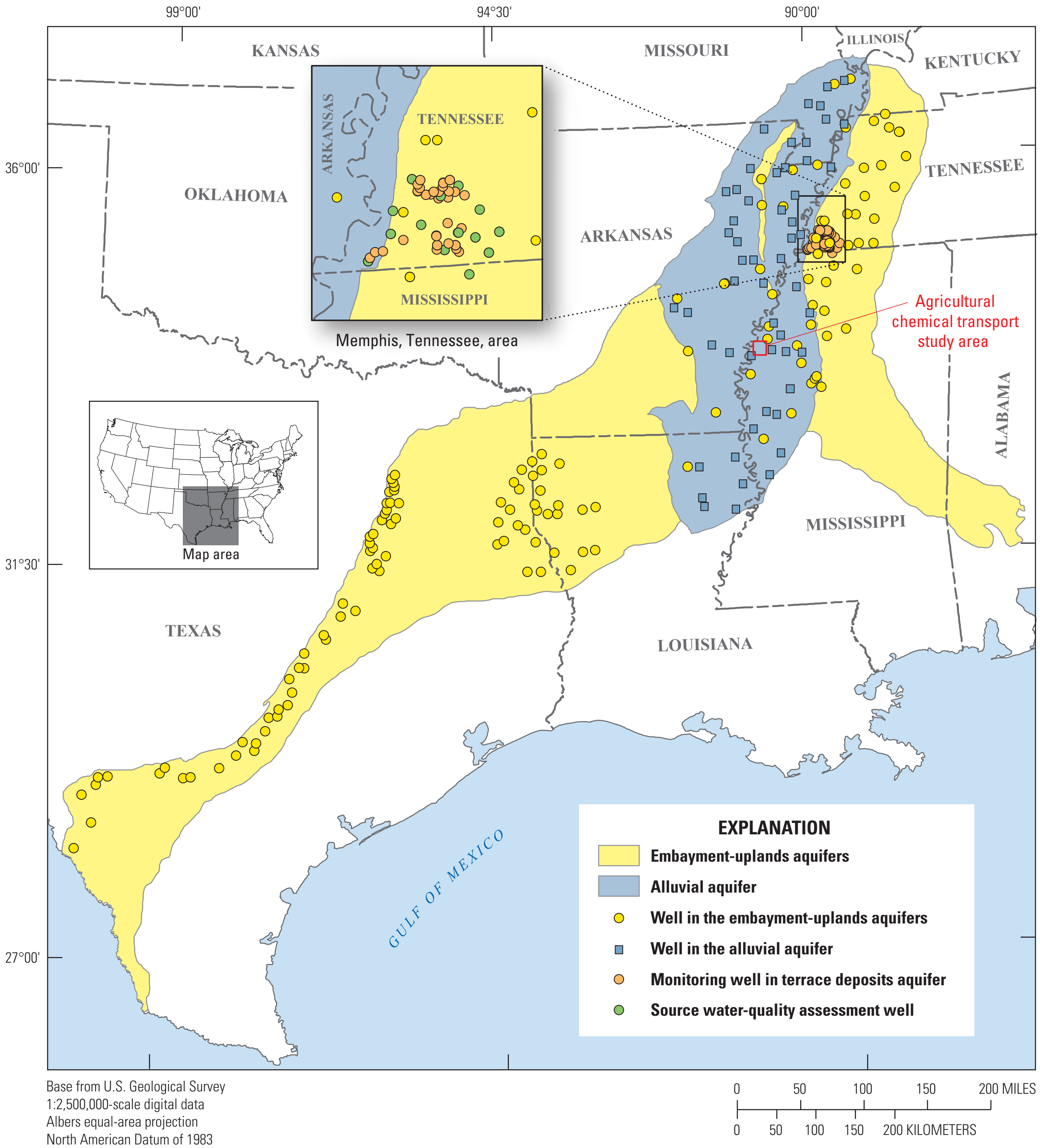


Figure 2–2. Most of the water samples for this assessment were collected from existing domestic, public-supply, and irrigation wells. An urban land-use study was done to characterize the quality of shallow groundwater in the Memphis, Tennessee, area.

To assess the quality of recently recharged groundwater underlying urban areas, one groundwater sample was collected in 1997 from each of 30 shallow monitoring wells installed by the USGS and a second sample was collected in 2006 in the Memphis, Tennessee, area (fig. 2–2). The urban land-use setting in this area is similar to that where many people work and live—single and multifamily residential and commercial development built between about 1970 and 1990. The wells are relatively shallow—from 33 to 109 ft deep (table 2–1)—and tap groundwater near the water table. The water quality of shallow groundwater is an indication of how the chemicals we use in day-to-day life—pesticides, solvents, gasoline—might someday affect the quality of the drinking-water resource.

Results for this assessment of groundwater are divided into shallow and deep groundwater. Groundwater tapped by wells 200 ft deep or less is classified as shallow, and groundwater tapped by wells greater than 200 ft deep is classified as deep. Shallow groundwater is more likely to be adversely affected by human activities at land surface than is deep groundwater. All of the wells in the alluvial aquifer and in the Memphis area were shallow (table 2–1). About half of the wells sampled in the embayment-uplands aquifers were deep wells used for drinking-water supply. In deep, confined parts of the embayment-uplands aquifers (fig. 2–3), groundwater likely is hundreds of years old and generally would not be affected by recent human activities at the land surface.

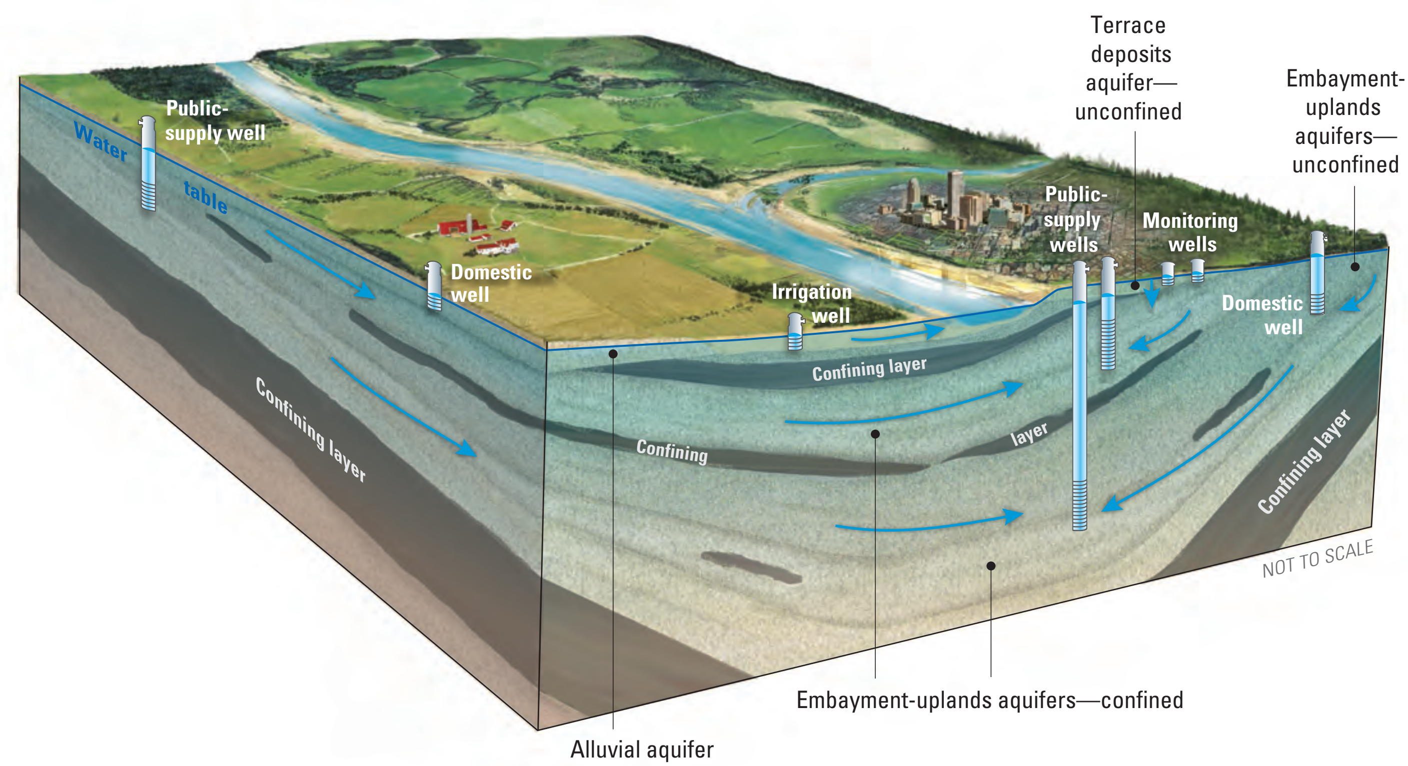


Figure 2–3. Wells in the embayment-uplands aquifers tap parts of the aquifers that represent a variety of hydrogeologic conditions. Wells 200 ft deep or less typically pump water from parts of the aquifers that are unconfined, and deeper wells typically pump water from confined parts of the aquifer system. None of the wells sampled in the overlying alluvial aquifer were more than 200 ft deep, but much of the alluvial aquifer is confined because it is overlain by fine-grained deposits that form an upper confining layer.

Aquifer (aq.ui.fer)—ăk'wə-fər

An underground layer of saturated permeable materials (rock, gravel, sand, or silt) that will yield a useful quantity of water to a well.

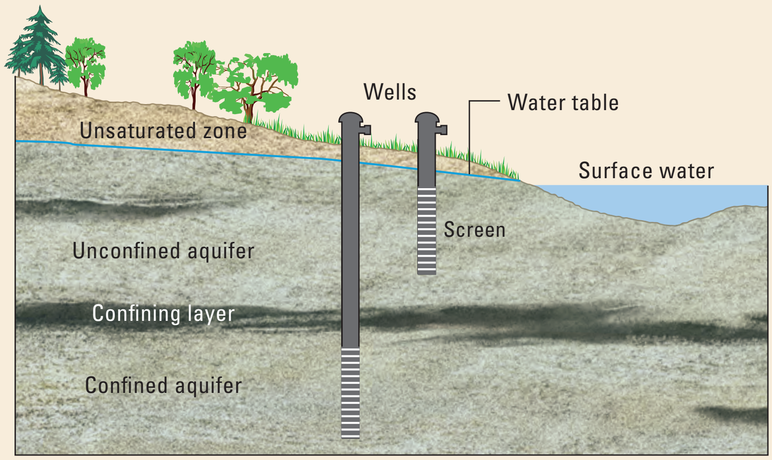
The **unsaturated zone** is the area below the land surface and above an aquifer. In addition to soil, rocks, and air, the unsaturated zone contains water from the land surface (such as rain) that is slowly moving downward to the water table of the aquifer.

An **unconfined aquifer** is bounded at its top by the water table, below which water fills all the pore spaces in the rock. Water from the land surface can move down into an unconfined aquifer.

A **confining layer** is a layer of material (often clay) through which water does not easily flow, creating a boundary between aquifers.

A **confined aquifer** is bounded at its top by a confining layer. Water enters or "recharges" confined aquifers where the confining layer is not present. Where the confining layer is not continuous or is breached (for example, by a well), flow between the unconfined and confined aquifer can occur.

The pressure within a confined aquifer can be greater than that in the overlying unconfined aquifer if the source of the water in the confined aquifer is at a higher elevation than the unconfined aquifer. In that case, water in a well in a confined aquifer will rise to a higher level than that in the overlying unconfined aquifer.



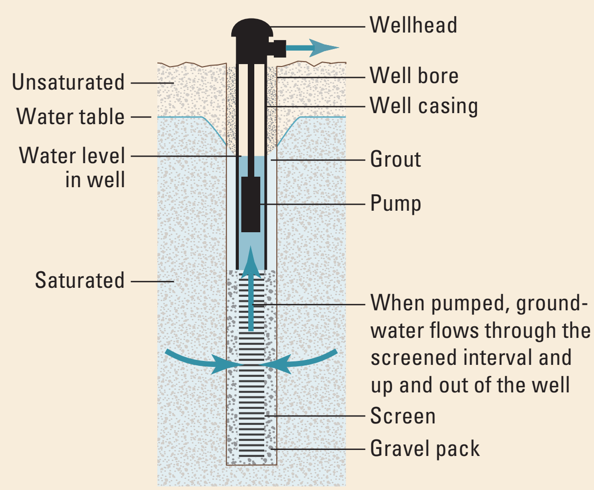
Sedimentary aquifer
Groundwater storage and flow between grains of sediment

Bedrock aquifer
Groundwater storage and flow in fractures

Carbonate aquifer
Groundwater storage and flow in solution cavities or fractures

Anatomy of a well

A well is simply a hole in the ground (well bore or borehole) from which water can be removed. The well bore is lined with a well casing, such as a pipe, to prevent the well bore from collapsing. The casing, along with a sealant (called grout), also prevents water from flowing into the well from the land surface or from parts of the aquifer where the water quality may be less desirable. The casing can be open at the bottom or perforated at a specific depth with a screen, to allow water to flow into the well where it can be pumped to the surface. Coarse sand or gravel (called sand pack or gravel pack) can be placed around the well screen to help improve the flow of water into the well. Some wells are cased only near the land surface, allowing water to flow into the well from nearly the entire length of the well bore.

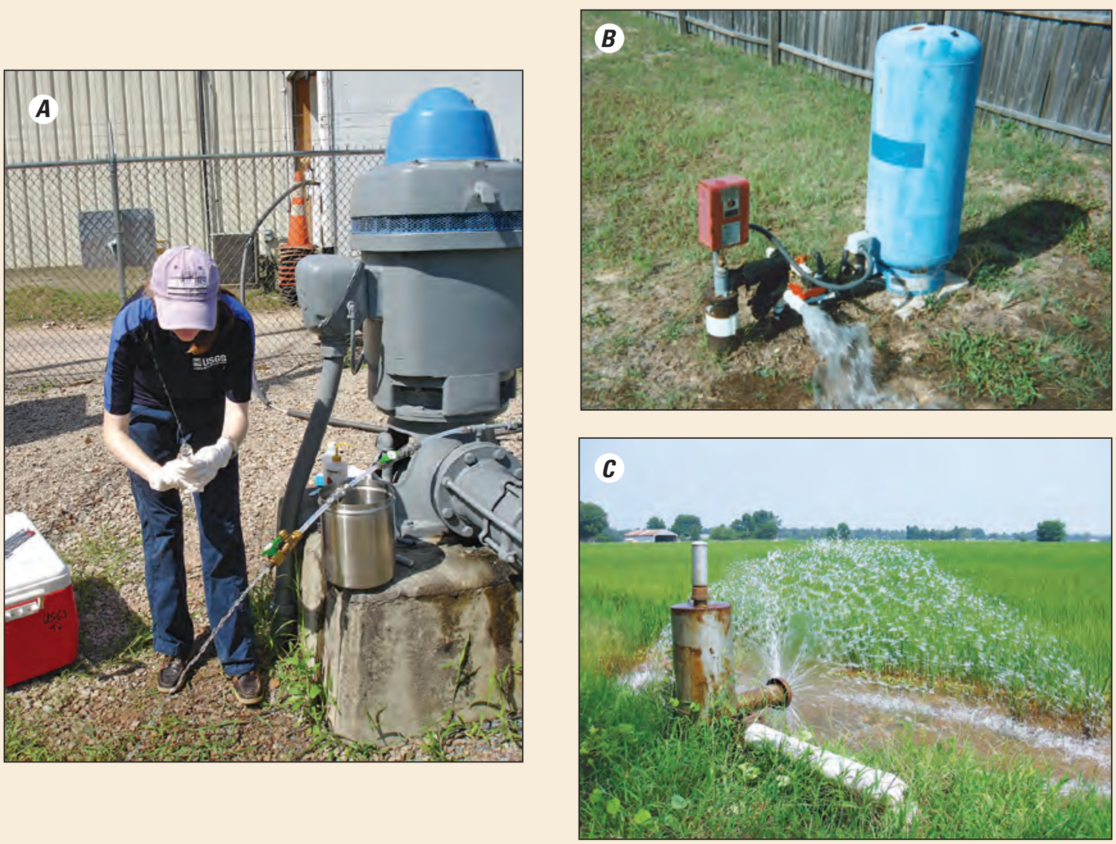


Does the type of well influence the quality of the groundwater sampled?

Two types of wells that supply drinking water were sampled: domestic (private) wells and public-supply wells. Domestic wells typically are shallower than public-supply wells and, therefore, pump water that is nearer to sources of manmade contaminants, such as fertilizers and pesticides, at the land surface. Domestic wells commonly are located in rural areas, which make them more vulnerable to contamination from agricultural chemicals than public-supply wells. Public-supply wells pump water from deeper in the aquifer and, therefore, are more likely to have higher concentrations of constituents from geologic sources, because deeper water generally has been in contact with the aquifer materials (sediments) for a longer period of time. Public-supply wells commonly are located in suburban and urban areas and, thus, are more likely than domestic wells to be vulnerable to contamination from chemicals associated with urban activities. Public-supply wells have larger pumps and longer screened intervals than do domestic wells and are pumped for longer periods of time. As a result, public-supply wells pump much larger volumes of water than do domestic wells and, thus, have much larger capture zones. Public-supply wells, therefore, are more vulnerable than domestic wells to manmade contamination from distant sources. If the amount of water withdrawn is large enough, it can change the flow direction and velocity of the groundwater, which in turn can affect the groundwater geochemistry and the constituents contained in the water. Water from domestic wells is not regulated, and homeowners are responsible for testing, maintaining, and treating the water from their domestic well. Water from public-supply wells is required to be tested by the well operator on a routine basis to help assure that the water provided to consumers meets Federal and State water-quality standards.

Groundwater samples also were collected from irrigation wells. Irrigation wells typically have pumping rates comparable to public-supply wells, but they generally are only pumped during the growing season. Because irrigation wells are located primarily in agricultural areas and often tap the shallowest water-bearing zone available, they are vulnerable to contamination from agricultural chemicals. Like public-supply wells, the high pumping rate of irrigation wells can lower groundwater levels and cause groundwater-flow directions in the aquifer to change, which in turn can affect groundwater geochemistry.

Finally, some groundwater samples were collected from monitoring wells. Monitoring wells are used for measuring water levels or occasionally for collecting water samples but are not routinely pumped for drinking water, irrigation, or other purposes. Monitoring wells sampled in the NAWQA groundwater studies were installed expressly for that purpose.



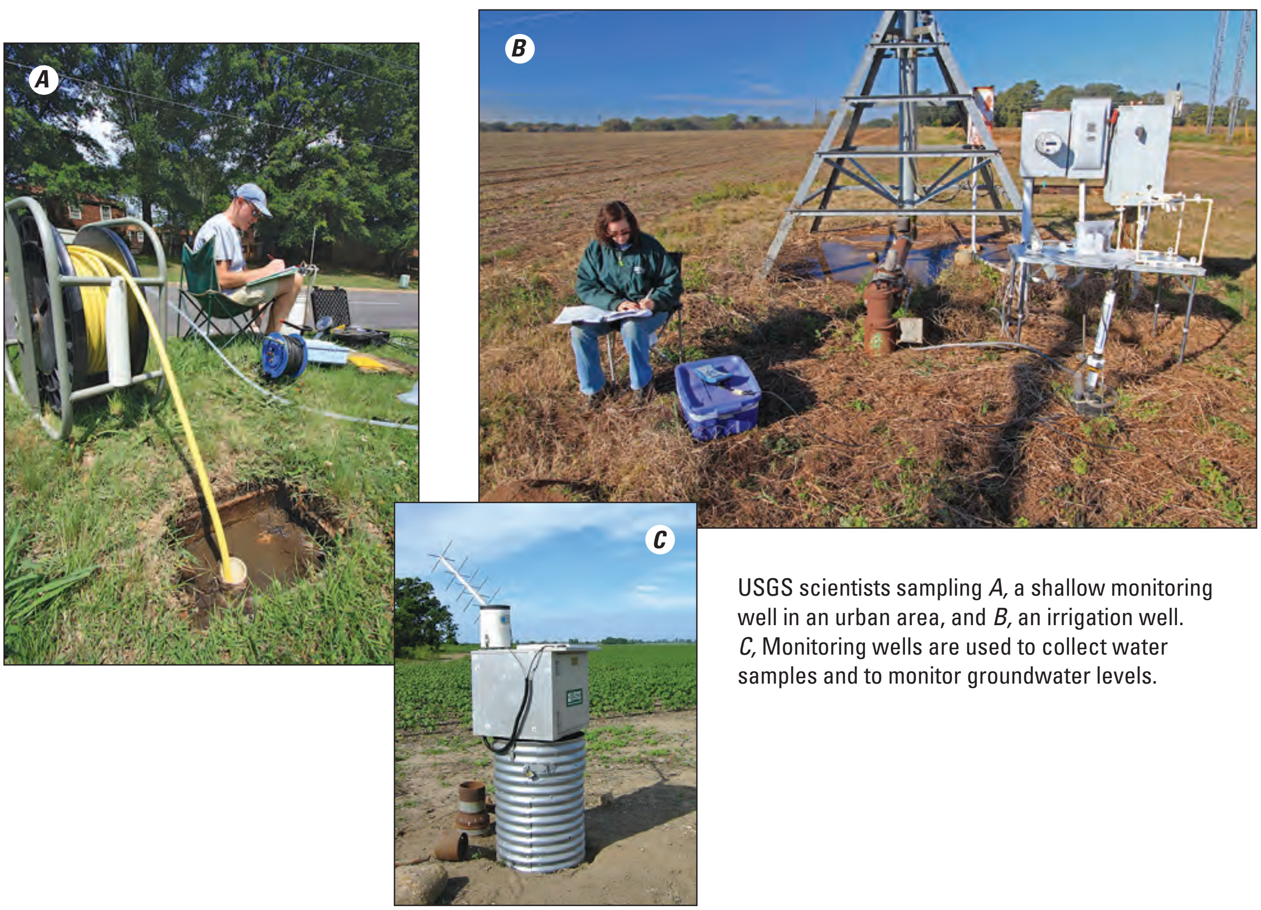
Photograph by Ralph Montanus, USGS

Several types of wells were sampled: *A*, public supply, *B*, domestic, and *C*, irrigation.

Understanding study results

Important aspects of the NAWQA Principal Aquifer assessments:

- Water samples were collected at the wellhead (see sidebar, Anatomy of a well, p. 11) prior to any treatment. They represent the quality of the groundwater resource but not necessarily the quality of tap water.
- The focus of the assessments is the condition of the total resource, including groundwater in a wide range of hydrologic and land-use settings across the Nation, rather than conditions at specific sites with known water-quality concerns.
- The assessments are guided by a nationally consistent study design, and all assessments use the same methods of sampling and analysis. Findings apply to water quality of a particular aquifer but also contribute to the larger picture of how and why water quality varies regionally and nationally. This consistent approach helps to determine if a water-quality issue is isolated or widespread. (See *http://water.usgs.gov/nawqa/about.html* for more information.)
- The assessments focus on aquifers used for water supply or on shallow groundwater that underlies an area with a particular type of land use. Because the NAWQA groundwater study areas do not cover the full spatial extent of the targeted Principal Aquifer, the findings might not represent the effects of the full range of geology, climate, and land use present.
- Analytical methods used by USGS chemists for assessments of water quality in Principal Aquifers are designed to measure constituents at as low a concentration as possible. As a result, constituents frequently are detected at concentrations far below human-health benchmarks for drinking water (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 30). Low-level detections allow scientists to identify and evaluate emerging issues and to track contaminant levels over time.



Photograph by Alan M. Cressler, USGS

Photograph by Alan M. Cressler, USGS

USGS scientists sampling *A,* a shallow monitoring well in an urban area, and *B,* an irrigation well. *C,* Monitoring wells are used to collect water samples and to monitor groundwater levels.

NAWQA assessments use a wide range of geochemical data and site information

Constituents measured in samples from most wells	
Constituent group	**Examples**
Water-quality properties	pH, specific conductance, dissolved oxygen, temperature
Major ions (filtered)	Bromide, calcium, chloride, magnesium, sodium, sulfate
Trace elements (filtered)	Arsenic, boron, iron, manganese, selenium, uranium
Nutrients (filtered)	Ammonia, nitrate, phosphorus
Pesticides (filtered)	Herbicides, insecticides, fungicides
Volatile organic compounds	Solvents, gasoline hydrocarbons, refrigerants, trihalomethanes, fumigants
Organic carbon (filtered)	
Additional constituents measured in samples from some wells	
Constituent group	**Examples**
Radionuclides	Radon
Groundwater age tracers	Tritium, chlorofluorocarbons
Stable isotopes	Oxygen-18, hydrogen-2
Microorganisms	*Escherichia coli* and total coliforms
Additional site information	
Use of well Well depth Depth to water Well-construction data Principal Aquifer	Land-surface elevation at well Land use within a 500-meter (1,640-foot) radius buffer Estimates of nutrient inputs Estimates of pesticide use

Chemists at the USGS National Water Quality Laboratory analyze groundwater samples using an array of sophisticated techniques.

Additional information (often called “ancillary information”) about the well and surrounding environment complements the chemical data measured. This additional information often is key to making sense of the chemical data. For example, the information might be used to determine that shallow groundwater is more (or less) vulnerable to contamination than deep groundwater, that domestic wells are more (or less) vulnerable to contamination than public-supply wells, or that urban land use is associated with different types of groundwater contamination than is agricultural land use. Chemical data without accompanying ancillary data are much less useful for understanding factors that affect groundwater quality.

Chapter 3: *Environmental and Hydrogeologic Setting*

The embayment-uplands aquifers extend from the southwest border of Texas to the southern tip of Illinois. The geology, climate, and topography vary over the large geographic extent of these aquifers, affecting recharge, groundwater flow, and, ultimately, the quality of groundwater. The alluvial aquifer of the Mississippi River Valley overlies much of the embayment-uplands aquifers. Hydrogeology and geochemical conditions in these aquifers affect the movement and fate of contaminants in groundwater. Activities associated with urban and agricultural land, such as groundwater pumping for public supply and irrigation, and the use of many chemicals in these settings have the potential to adversely affect water quality. Understanding the natural environmental and hydrogeologic system and the effects of human activities on groundwater is essential for assessing the vulnerability of groundwater resources to contamination.

This chapter summarizes background information for the embayment-uplands and alluvial aquifers and provides the context for understanding findings about water quality in these Principal Aquifers. The chapter covers the environmental and hydrogeologic setting, including population, land use, and water use.

"Water pump and a tractor power plant, a common sight in the rice area in Arkansas. In some places in the state, the pumps go down more than one hundred feet and pump constantly the entire period during which the rice is grown. Each year, so much water is drawn out that the pump must be sunk another two or three feet."

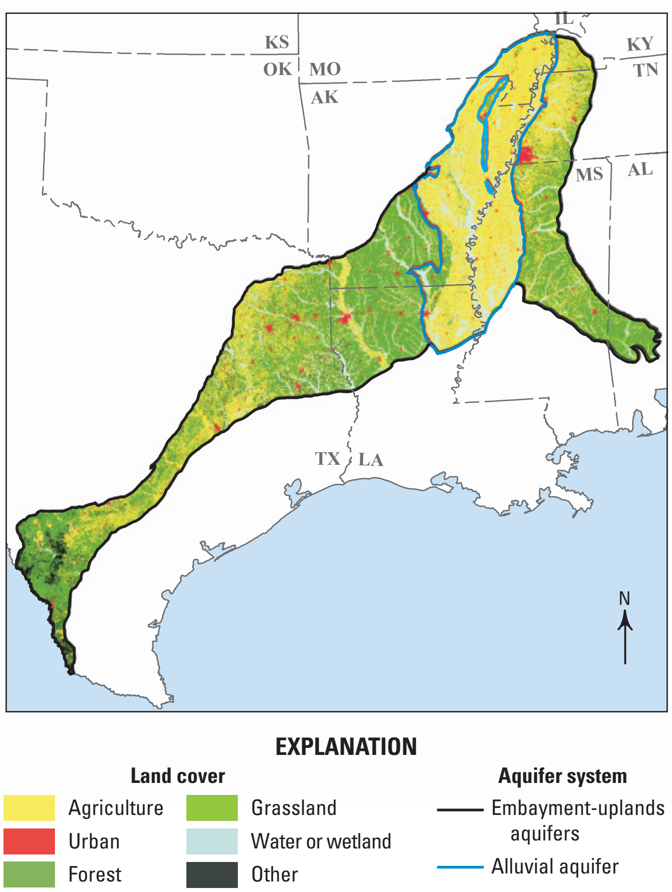
Description for a 1936 photograph by Carl Mydans showing irrigation of rice fields in Arkansas.

Photograph from Library of Congress Prints and Photographs Division, *http://www.loc.gov/pictures/item/fsa1998020199/PP/*

Environmental Setting

Groundwater quality varies naturally across the extent of regional aquifers because of differences in hydrogeology, including the composition of aquifer materials, the amount of recharge, and the length of groundwater-flow paths. The study area covers a large area—about 197,000 square miles (mi^2) in parts of nine States in the south-central United States (Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas)—and includes the embayment-uplands aquifers and alluvial aquifer (fig. 3–1). The topography is characterized by flat to gently rolling terrain.

Climate in the study area varies from semiarid in southwest Texas to humid subtropical in the east and southeastern part of the study area. Average annual precipitation ranges from about 20 inches per year in the extreme southwestern part of the study area to between 50 and 60 inches per year in the eastern and northern parts. These differences in climate across the embayment-uplands aquifers are reflected in the groundwater quality. For example, concentrations of dissolved solids typically are higher in semiarid areas with little rainfall than in more humid areas with larger amounts of rainfall.



Modified from Homer and others[4]

Figure 3–1. Land use in the study area is dominated by agriculture and forest with much of the row-crop agriculture concentrated in the areas overlying the alluvial aquifer.

Hydrogeologic Setting

The embayment-uplands aquifers consist of five regional aquifers that are separated in many places by regional confining layers (appendix 2). This water-quality assessment focuses primarily on three of the embayment-uplands aquifers—the middle Claiborne, lower Claiborne-upper Wilcox, and middle Wilcox aquifers—and the alluvial aquifer, which overlies the embayment-uplands aquifers in the central part of the study area (fig. 3–2). The embayment-uplands aquifers consist of thick beds of primarily unconsolidated sand with interbedded lenses of silt and clay. A regional upper confining layer, present throughout much of the study area, separates the embayment-uplands aquifers from the overlying alluvial aquifer and the Coastal lowlands aquifer system to the south. In many areas, the embayment-uplands aquifers are overlain by shallow aquifers that typically are less than 100 ft thick. In this report, a local shallow aquifer in the Memphis area—the terrace deposits aquifer—is considered to be part of the embayment-uplands aquifers. A lower confining layer separates the lower Wilcox aquifer from underlying aquifers in geologic units of Cretaceous age, which in this report are not included in the embayment-uplands aquifers. An intermediate regional confining layer separates the middle Claiborne and lower Claiborne-upper Wilcox aquifers in Louisiana, Mississippi, and parts of Arkansas.[5] In the northern part of the study area, the aquifers dip toward the Mississippi River on both the east and west sides and thicken in the down-dip direction. In the southern part of the study area, the aquifers dip and thicken toward the Gulf of Mexico.

In the central part of the study area, the embayment-uplands aquifers are overlain by the alluvial aquifer (fig. 3–2). Throughout much of the Mississippi River alluvial valley an upper layer of fine-grained deposits impedes downward flow of water and is an upper confining layer for the alluvial aquifer. The alluvial aquifer generally is less than 200 ft thick but is very productive. Where a confining layer between the embayment-uplands aquifers and the alluvial aquifer is thin or absent, these aquifers are connected. The alluvial aquifer is made up of two subunits of different geologic age and composition: the Holocene alluvium, which is associated with more recent deposition, and Pleistocene valley train deposits.

Recharge to the embayment-uplands aquifers occurs predominantly by the infiltration of rainfall in areas where the aquifer sediments are exposed at land surface. In areas where groundwater withdrawals have lowered water levels, recharge also can occur from streams or from downward movement of water from the overlying alluvial aquifer and other shallow aquifers. Groundwater flows from areas of recharge to points of discharge (primarily major rivers and pumped wells) along regional flow paths that tend to follow the slope of the geologic units. In some areas, groundwater flow is affected by geologic structures, such as faults and areas of uplift, and also by salt domes, particularly in parts of Texas and Louisiana.

Vulnerability of groundwater to contamination depends on the physical properties of the groundwater-flow system as well as the locations and types of natural and human sources of contamination, relative location of wells, and fate and transport of contaminants.[6]

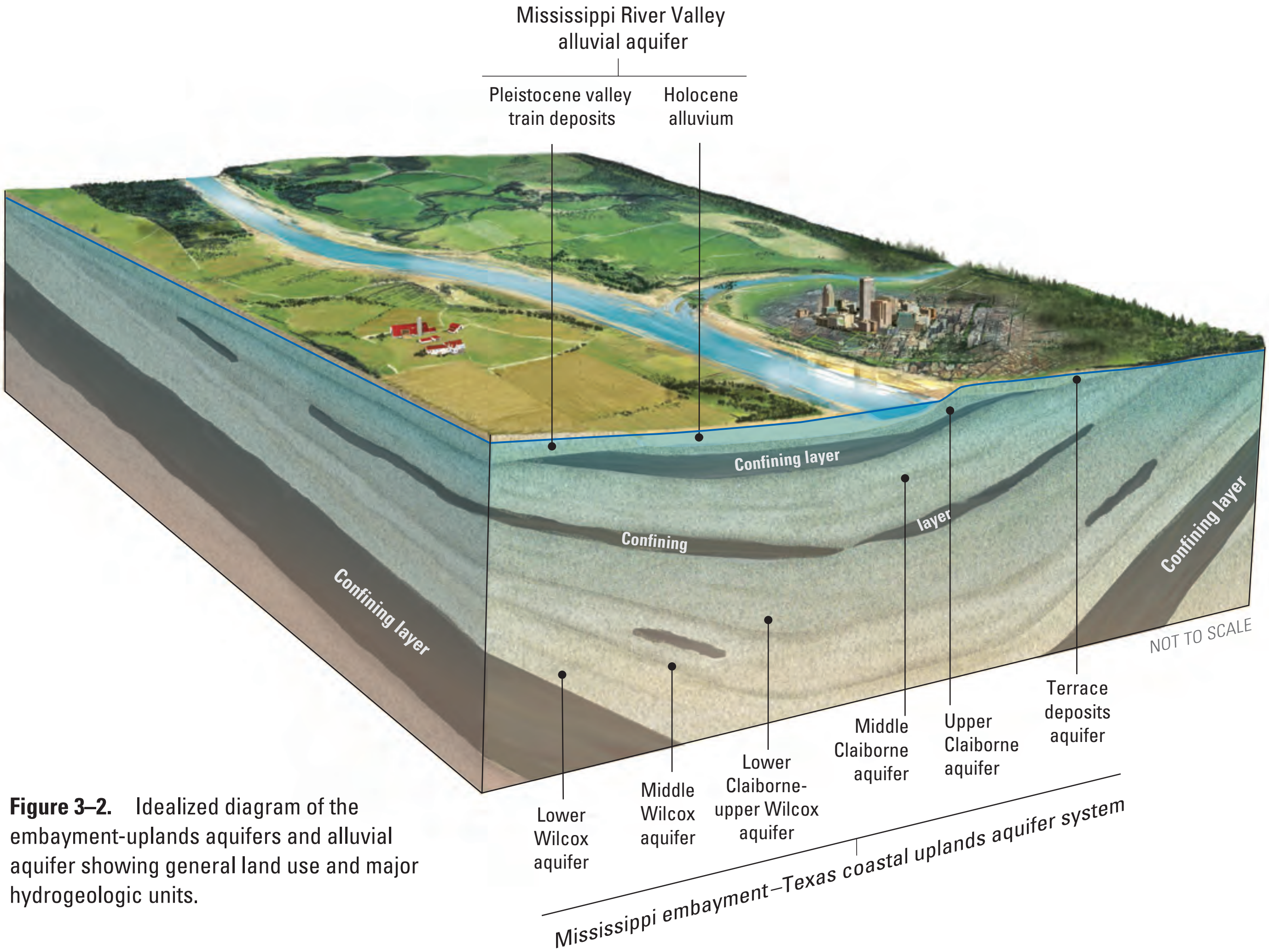


Figure 3–2. Idealized diagram of the embayment-uplands aquifers and alluvial aquifer showing general land use and major hydrogeologic units.

Recharge to the overlying alluvial aquifer occurs from the infiltration of rainfall and water from the Mississippi River and other streams that are connected to the aquifer. The upper layer of fine-grained sediments serves as an upper confining layer and limits the amount of recharge to the alluvial aquifer in many areas. The general direction of groundwater flow in the alluvial aquifer is toward major streams that receive groundwater discharge, but some groundwater moves downward into the embayment-uplands aquifers. Withdrawals from wells in the alluvial aquifer have reduced the amount of discharge to streams and increased the amount of recharge to the aquifer.[5]

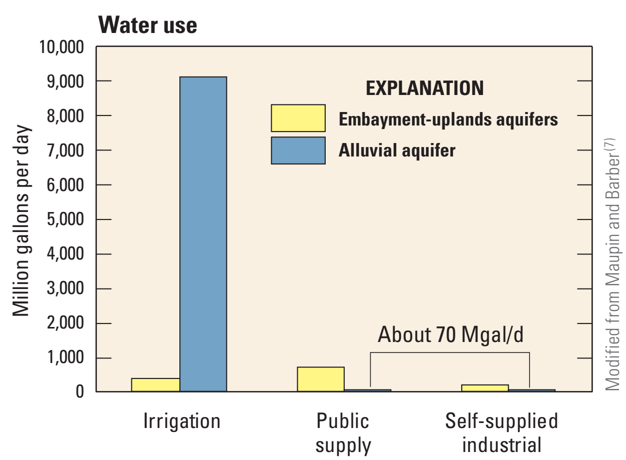
Land Use and Water Use

Because recharge moves from the land surface into the underlying aquifers, land use can have a major effect on groundwater quality. In both urban and agricultural areas, the use of chemicals and their release to the environment, either inadvertently or intentionally (as is the case for pesticides and fertilizer), can adversely affect groundwater quality. Much of the study area is rural—about 41 percent is agricultural land (cultivated crops, small grains, fallow, and pasture/hay) and 37 percent is forested land (fig. 3–1). Agricultural land is concentrated in the floodplain of the Mississippi River and its tributaries and is used primarily for soybean, cotton, corn, and rice cultivation.

Groundwater is the primary source of drinking water for most of the nearly 10 million people that live in the study area. About 800 million gallons per day (Mgal/d) of groundwater were pumped for public supply in 2000 (fig. 3–3), of which about 90 percent was withdrawn from the embayment-uplands aquifers.[7] Some of the largest withdrawals for public supply are in West Tennessee, particularly in the Memphis area, and in parts of northwestern Mississippi, north-central Louisiana, and southern and eastern Arkansas. Water use for domestic supply is distributed throughout the study area, and total withdrawals from domestic wells are small compared to withdrawals for public supply. An estimated 100 Mgal/d were withdrawn from the embayment-uplands aquifers for domestic use in 2005—about 8 times less than for public supply.[8]

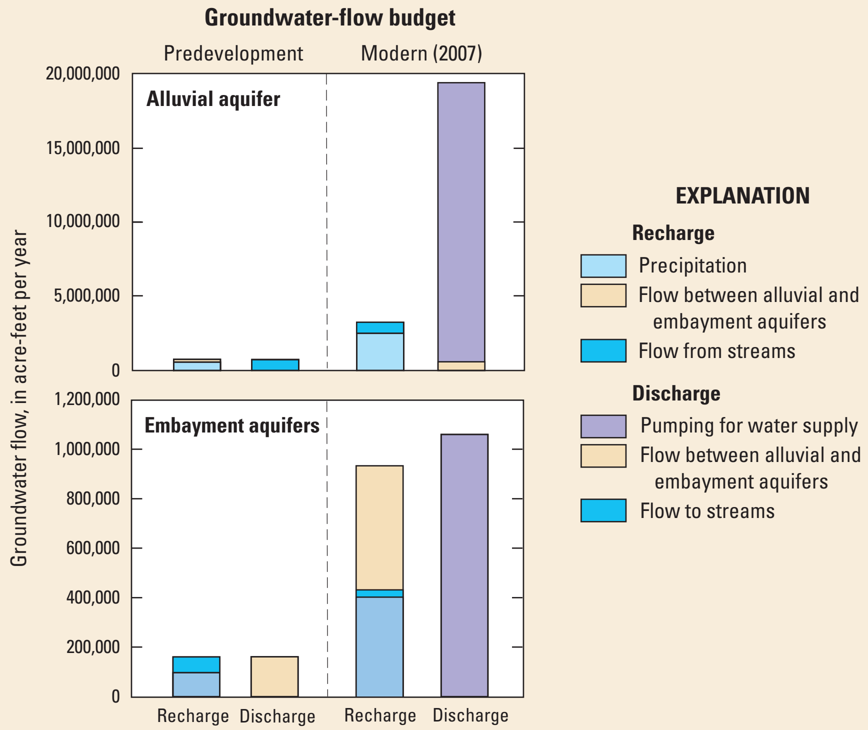
The aquifers in the study area are important sources of water for irrigation and industrial uses, and long-term use of this resource has lowered groundwater levels. Since the development of groundwater as a source of water supply in the late 1800s and early 1900s, large groundwater withdrawals from the embayment-uplands aquifers in the Memphis area, northern Louisiana, and southern Arkansas have lowered groundwater levels as much as 300 ft and caused downward movement of groundwater from the alluvial aquifer and other local water-table aquifers to the embayment-uplands aquifers.[5, 9] Withdrawals from the alluvial aquifer for irrigation are the third largest in the Nation and were considerably greater than estimates of other uses of water in the study area (fig. 3–3). The large amounts of pumping from the alluvial aquifer also have resulted in water-level declines and have decreased the amount of water stored in the aquifer (see sidebar, Long-term pumping for irrigation, public supply, and industrial use has changed groundwater-flow budgets, p. 19).

Figure 3–3. Public water supply is the dominant water use in the embayment-uplands aquifers, but considerably more water is used for irrigation from the alluvial aquifer.[7] Withdrawals for irrigation from the alluvial aquifer are the third largest in the Nation. The availability of water from both of these Principal Aquifers is important to the agricultural economy of the region and for the continued use as the primary source of drinking water.



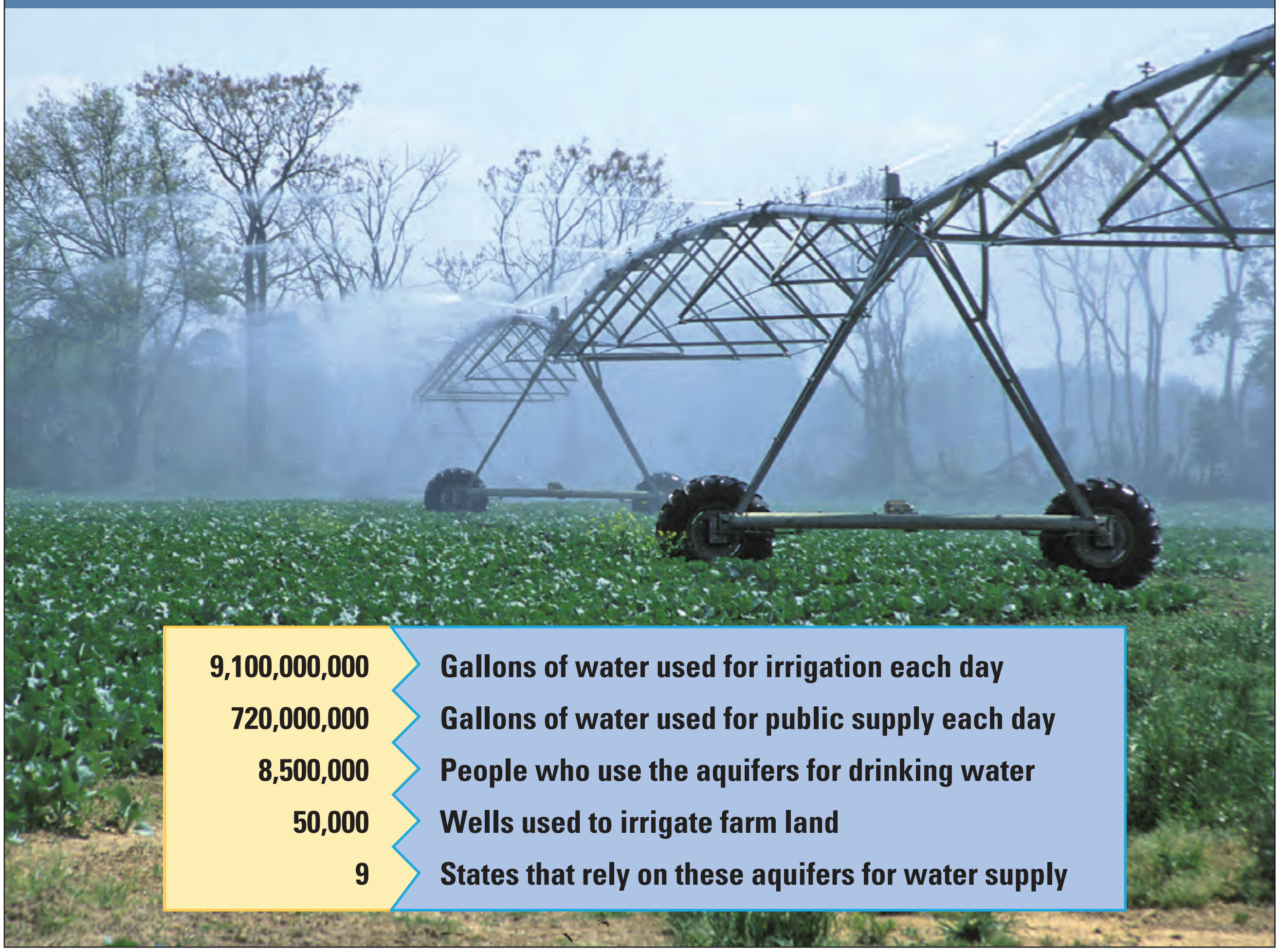
Long-term pumping for irrigation, public supply, and industrial use has changed groundwater-flow budgets

Large withdrawals of groundwater over many years for irrigation, public supply, and industrial use have profoundly changed how water flows through the alluvial and underlying embayment aquifers. These changes can be estimated by using a groundwater-flow-model water budget, which quantifies the amount of water that enters, leaves, and is stored in an aquifer.[35] Prior to groundwater pumping (predevelopment), water in the alluvial aquifer primarily discharged to streams, and this outflow was balanced by recharge from rainfall and the upward movement of water from the underlying embayment aquifers. Recharge and discharge were similarly balanced for the embayment aquifers. In modern times, the amount of water pumped from both of the aquifers exceeds the amount of recharge. As a result, water stored in the aquifers is being removed, and water levels are declining. Streams that used to be fed by discharge from the alluvial aquifer now lose water to the aquifer. The direction of groundwater flow between the embayment aquifers and the alluvial aquifer has reversed, with water in the alluvial aquifer draining downward instead of water in the embayment aquifers discharging upward. The changes in the water budget have increased the vulnerability of both of these aquifers to surface contamination and could result in adverse changes in water quality from deep water if water with high dissolved solids (saline water) moves into areas of fresh groundwater in the embayment aquifers. Understanding how groundwater-flow budgets change with water use is critical to the sustainability of these important resources in terms of both quantity and quality.



Estimates of predevelopment and modern groundwater-flow budgets for the alluvial aquifer and embayment aquifers show large changes in recharge, groundwater storage, and the amount of water discharging to streams as a result of large, long-term pumping for irrigation, public supply, and industrial use.

The embayment-uplands and alluvial aquifers at a glance



9,100,000,000	Gallons of water used for irrigation each day
720,000,000	Gallons of water used for public supply each day
8,500,000	People who use the aquifers for drinking water
50,000	Wells used to irrigate farm land
9	States that rely on these aquifers for water supply

Photograph by Jeff Vanuga, USDA NRCS

Chapter 4: *Natural Processes and Human Activities That Affect Groundwater Quality*

This chapter summarizes and explains the hydrologic and geochemical processes and human activities that affect the movement and quality of groundwater in the embayment-uplands and alluvial aquifers.

Aspects of aquifer hydrogeology, such as the presence of confining layers and groundwater residence times, are important controls on water quality in the embayment-uplands and alluvial aquifers. Water quality in these aquifers also is affected by geochemical processes and conditions, such as the presence or absence of dissolved oxygen and the resulting reduction-oxidation (redox) conditions, which can affect the solubility and fate of numerous constituents. In addition to natural processes, human activities, such as pumping for public supply, can affect water quality by changing groundwater flow within and between aquifers.

Where the formations that make up the embayment-uplands aquifers are at land surface or at shallow depths, the aquifers typically are unconfined and vulnerable to contamination from human-related sources at land surface.

Confining Layers Limit the Movement of Contaminants Into Aquifers

The presence of regional confining layers is one of the primary factors affecting the quality of water in both the embayment-uplands aquifers and the alluvial aquifer. Layers of clay and silt with lower permeability than the sand and gravel that make up the aquifers slow the vertical movement of groundwater from the land surface or between aquifers. In the embayment-uplands aquifers, recharge to the aquifers occurs primarily in areas where the aquifers are exposed at or near the land surface (see chapter 3) and groundwater follows flow paths downgradient to parts of the aquifers that are confined. Fine-grained sediments at the top of the Mississippi River alluvium in most locations serve as an upper confining layer to the aquifer. This overlying confining layer slows the rate of recharge and limits vertical transport of contaminants from the land surface into the aquifer. Groundwater in these aquifers, therefore, is most vulnerable to contamination from manmade contaminants in areas where the confining layers are thin or absent.

Much of the Groundwater Used for Drinking Water Is Relatively Old

Groundwater flows slowly through the embayment-uplands aquifers and the alluvial aquifer at rates of generally less than 1 ft to a few feet per day. In many areas where the embayment-uplands aquifers are the primary source of water for public supply, the groundwater residence time is long and water pumped from a well might have entered the aquifer decades or even centuries ago (fig. 4–1). In shallow parts of the aquifers, or in outcrop areas, groundwater residence times can be less than 50 years. For the purposes of this report, groundwater with an apparent age of less than 50 years is considered “young” groundwater. The parts of these aquifers where groundwater is younger than 50 years old are the most vulnerable to contamination from human activities at land surface because flow paths from the land surface are short.

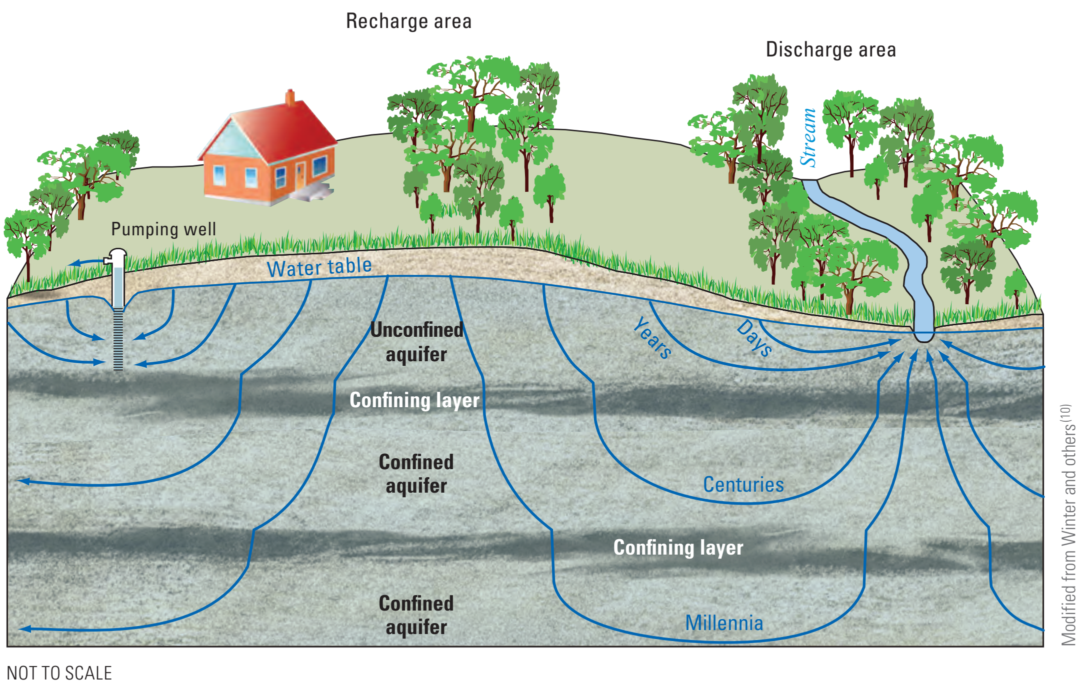


Figure 4–1. The amount of time groundwater is in an aquifer (groundwater residence time) depends on the flow path along which the water moves. Groundwater can take from days to millennia to flow from points of recharge at land surface to points of discharge at, for example, a pumping well or a stream.

Aquifer Sediments Can Be a Source of Dissolved Constituents in Groundwater

The water quality of the embayment-uplands aquifers and alluvial aquifer is affected by the interaction of the water and sediments that make up these aquifers and confining layers. As dilute recharge water moves into and through aquifer sediments, it reacts with minerals in the sediments, causing major ions, such as calcium, magnesium, and sulfate, and trace elements, such as arsenic, to dissolve into the groundwater. The minerals in the sediments and the groundwater residence time determine the extent to which these reactions will occur and what the resulting concentrations of dissolved solids in the groundwater will be. Typically, the longer the flow path and groundwater residence time, the more mineralized the water will become. The embayment-uplands aquifers that were sampled for this assessment consist predominantly of quartz sand, which is not very reactive. Thus, despite relatively long flow paths, the total dissolved solids content of groundwater remains low in many parts of these aquifers. In contrast, the sediments that make up the alluvial aquifer are more heterogeneous than the sediments in the embayment-uplands aquifers and include carbonate minerals that dissolve more readily than quartz. As a result, groundwater in the alluvial aquifer has higher concentrations of dissolved solids even though flow paths and groundwater residence times are shorter than those in deep parts of the embayment-uplands aquifers.

Redox Conditions Affect the Occurrence and Fate of Contaminants

The occurrence and fate of many contaminants, both manmade and those with geologic sources, often are controlled by the redox conditions in an aquifer. The fate and transport of nitrate in groundwater depends on the redox conditions in the aquifer because under anoxic conditions nitrate is converted to nitrogen gas through denitrification (see sidebar, How do redox reactions work? p. 24). Redox conditions also affect the occurrence of several other inorganic contaminants. Iron or manganese oxides that coat the surfaces of aquifer sediments often bind other trace elements, such as arsenic, to the aquifer sediments. Under reducing conditions, iron and manganese oxides dissolve, which increases their concentrations in groundwater and may release arsenic or other trace elements. Groundwater in many parts of the embayment-uplands and alluvial aquifers is confined (fig. 4–2). As groundwater moves along a flow path, the dissolved oxygen that entered the aquifer with recharge is consumed. Confining layers prevent additional recharge and dissolved oxygen from entering the aquifer, and redox conditions become more reducing with increasing groundwater residence time and distance from recharge areas along a flow path.

Groundwater Pumping Can Affect Water Quality

Pumping of groundwater for public supply, industrial uses, and irrigation can affect the quality of groundwater in the embayment-uplands aquifers and alluvial aquifer. Groundwater flow within and between aquifers is affected when withdrawals for these uses are large enough to cause persistent water-level declines. Water-level declines can cause downward movement of shallow groundwater that may be contaminated from activities on the land surface, such as the use of fertilizers and pesticides in urban and agricultural areas. Conversely, in some areas, pumping can cause water of poor quality at great depths to move upward into the parts of the aquifer used as a source of drinking water.

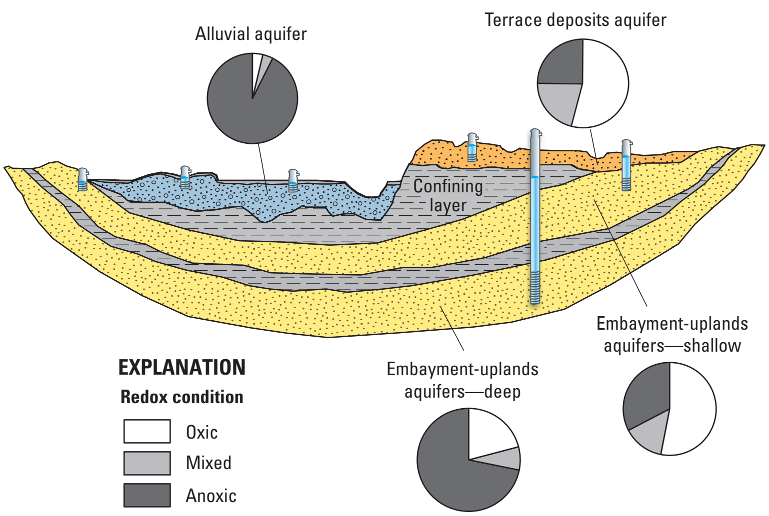
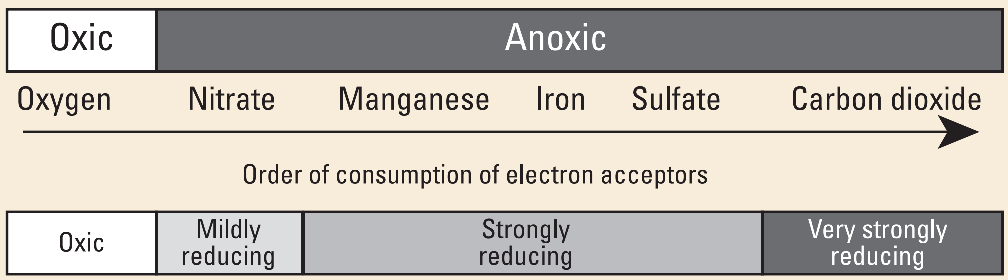


Figure 4–2. Redox conditions are largely anoxic in the alluvial aquifer and deep parts of the embayment-uplands aquifers because of overlying confining layers, which prevent water containing dissolved oxygen from infiltrating into the aquifers in these areas.

How do redox reactions work?

Reduction/oxidation (redox) processes require one chemical species that donates electrons and another chemical species that accepts those electrons. As a chemical species donates electrons it is “oxidized,” and as the other species accepts electrons it is “reduced.” Redox processes typically are facilitated by microbes (bacteria), which use the energy produced by the processes. In groundwater, organic carbon is the most common electron donor. If dissolved oxygen is present, it is the preferred electron acceptor, because reduction of dissolved oxygen produces more energy than reduction of other chemical species that commonly occur in groundwater. The atmosphere is the source of the dissolved oxygen, so the redox conditions in an aquifer near where recharge occurs usually are oxic (defined here as having a concentration of dissolved oxygen of at least 0.5 mg/L).



As groundwater moves through the aquifer along a flow path, the dissolved oxygen in the groundwater gradually is consumed by redox processes. Once all of the dissolved oxygen is consumed, other chemical species can accept electrons and become reduced. If nitrate is present, it will become the preferred electron acceptor until it in turn is completely consumed. This pattern continues, with manganese, iron, sulfate, and finally carbon dioxide acting as electron acceptors until they are consumed, in that order. This order of use of electron acceptors has important implications for the preservation, degradation, and even production of contaminants in groundwater. Because redox reactions occur in a sequence, it can take a long time for strongly reducing conditions to develop. For this reason, anoxic groundwater commonly is older than oxic groundwater, and, within the anoxic category, strongly reducing groundwater commonly is older than mildly reducing groundwater.

From a water-quality perspective, denitrification—the reduction of nitrate to nitrogen gas—is one of the most important redox processes that occurs in groundwater. Nitrate is a concern for human health and, where it discharges to surface water, can impair aquatic communities. Conversion of nitrate by denitrification to harmless nitrogen gas, the same gas we breathe in the atmosphere, is the primary way that nitrate is removed from water.

Chapter 5: *Quality of the Groundwater Resource Used for Drinking*

Few contaminants were detected in samples of groundwater from the embayment-uplands and alluvial aquifers at concentrations approaching or greater than human-health benchmarks. Constituents derived from geologic sources were detected more frequently at concentrations approaching benchmarks than those derived from human sources.

This chapter provides a summary of constituents that were detected at a concentration greater than or near a human-health benchmark in water from drinking-water supply wells tapping the embayment-uplands and alluvial aquifers.

Few Contaminants From Geologic Sources Were Detected at Concentrations Greater Than a Human-Health Benchmark

Only nine of the constituents analyzed for the assessment of groundwater quality were detected at a concentration greater than a human-health benchmark (see sidebar, Human-health benchmarks and other guidelines used in this assessment, p. 30) in at least one sample from a drinking-water well. Six of these nine contaminants exceeded benchmarks in 2 percent or less of samples.

Radon and manganese were the only contaminants measured at concentrations that exceeded a benchmark in more than 10 percent of samples (table 5–1). Regulation of radon was proposed by the USEPA in 1999 with a Maximum Contaminant Level (MCL) of 300 picocuries per liter (pCi/L) for public water systems in States without programs to mitigate risk from other sources of radon, and with an alternative MCL of 4,000 pCi/L that would apply to water systems in areas that have multimedia mitigation programs. Concentrations of radon exceeded the proposed MCL of 300 pCi/L in about 30 percent of the wells sampled, most of which were in samples from the embayment-uplands aquifers. No concentrations of radon, however, exceeded the proposed alternative MCL of 4,000 pCi/L. Concentrations of manganese were greater than the Health-Based Screening Level (HBSL) concentration of 300 micrograms per liter (µg/L) in about 12 percent of the drinking-water wells sampled. About 75 percent of these elevated manganese concentrations were in wells screened in the alluvial aquifer.

The differences in occurrence of elevated concentrations of the contaminants reflect differences in the composition of sediments that make up the embayment-uplands and alluvial aquifers and the geochemistry of these aquifers. Radon is a radioactive gas, and its occurrence in groundwater is related to the presence of uranium-bearing minerals in the sediments of the embayment-uplands aquifers. Manganese is relatively insoluble in oxic groundwater (dissolved oxygen $\geq$0.5 mg/L), but its solubility increases

Table 5–1. Few contaminants were detected at concentrations greater than human-health benchmarks. Constituents with geologic sources were detected more commonly at concentrations approaching benchmarks than contaminants related to human activities.

[MCL, Maximum Contaminant Level; AMCL, alternative Maximum Contaminant Level; HBSL, Health-Based Screening Level; pCi/L, picocurie per liter; µg/L, microgram per liter; N, nitrogen; mg/L, milligram per liter; —, not applicable; <, less than]

Constituent	Benchmark concentration	Type of benchmark	All wells: Number of samples	All wells: Percentage of samples with concentrations that exceeded Benchmark	All wells: Percentage of samples with concentrations that exceeded One-tenth of benchmark	Drinking-water wells: Number of samples	Drinking-water wells: Percentage of samples with concentrations that exceeded Benchmark	Drinking-water wells: Percentage of samples with concentrations that exceeded One-tenth of benchmark	Monitoring wells in urban area: Number of samples	Monitoring wells in urban area: Percentage of samples with concentrations that exceeded Benchmark	Monitoring wells in urban area: Percentage of samples with concentrations that exceeded One-tenth of benchmark
Constituents from geologic sources											
Radon	300 pCi/L	Proposed MCL	167	29	—	101	37	—	26	35	—
Radon	4,000 pCi/L	Proposed AMCL	167	0	—	101	0	—	26	0	—
Manganese	300 µg/L	HBSL	227	22	52	143	12	42	33	12	47
Arsenic	10 µg/L	MCL	199	3	22	115	<1	11	33	0	3
Radium*	5 pCi/L	MCL	129	2	29	90	3	37	13	0	0
Strontium	4,000 µg/L	HBSL	119	<1	31	81	1	41	30	0	3
Contaminants related to human activities											
Dieldrin	0.002 µg/L	HBSL	242	2	2	157	<1	<1	33	12	12
Lead	15 µg/L	Action level	199	1	9	115	2	15	33	0	0
Nitrate as N†	10 mg/L	MCL	226	<1	15	143	0	12	33	0	47
Zinc	2,000 µg/L	HBSL	185	<1	3	101	1	3	33	0	0

*Radium 226 and radium 228 combined. Evaluated at 1 pCi/L instead of one-tenth of the benchmark because of laboratory reporting level.

†Nitrate occurs in groundwater naturally, but concentrations greater than 1 mg/L as N indicate anthropogenic inputs of nitrogen in many aquifers across the Nation.[11]

in the anoxic conditions (dissolved oxygen <0.5 mg/L) present throughout most of the alluvial aquifer. Other constituents derived from geologic sources that were measured at concentrations greater than human-health benchmarks were arsenic (see chapter 6), strontium, and radium. The percentage of samples with concentrations greater than the benchmark concentration for these contaminants was less than 4 percent; however, as many as 30 percent of the samples had concentrations exceeding one-tenth the benchmark (table 5–1).

Concentrations of five constituents (aluminum, chloride, dissolved solids, iron, and fluoride) were detected at concentrations greater than the Secondary Maximum Contaminant Levels (SMCLs; table 5–2), which are recommended values for nuisance constituents in drinking water that can cause unpleasant taste and odor, stain laundry and fixtures, or corrode pipes. Although the elevated concentrations of these constituents do not represent a potential concern for human health, their occurrence in groundwater could limit the uses of water or result in additional cost for treatment.

Table 5–2. Concentrations of manganese and iron were greater than the Secondary Maximum Contaminant Level in more than 30 percent of samples from drinking-water wells. Elevated concentrations can cause unpleasant taste and odor and stain laundry and plumbing fixtures, resulting in the need for additional water treatment or increasing water-treatment costs.

[SMCL, Secondary Maximum Contaminant Level; µg/L, microgram per liter; mg/L, milligram per liter; <, less than]

Constituent	Benchmark concentration	All wells		Drinking-water wells		Monitoring wells in urban area	
		Number of samples analyzed	Percentage of samples exceeding SMCL	Number of samples analyzed	Percentage of samples exceeding SMCL	Number of samples analyzed	Percentage of samples exceeding SMCL
Manganese	50 µg/L	227	48	143	34	33	47
Iron	300 µg/L	227	44	143	36	33	25
Dissolved solids	250 mg/L	227	19	143	22	33	3
Aluminum	0.05 – 0.2 mg/L	184	3	103	7	33	0
Chloride	250 mg/L	227	1	143	2	33	0
Fluoride	2 mg/L	227	<1	143	<1	33	0

Chapter 5

What is a contaminant?

Contaminants have a wide range of sources, both manmade and geologic. Most organic chemicals in groundwater that are of concern for human health are manmade. In contrast, most inorganic constituents in groundwater have geologic or other natural sources, although their concentrations in groundwater may be altered by human activities, such as irrigation and groundwater pumping. Some contaminants have both manmade and natural sources. For example, nitrate in groundwater has many natural sources, but nitrate concentrations in groundwater underlying agricultural and urban areas commonly are higher than in other areas because of contributions from sources associated with human activities.

But what exactly is a contaminant? The word means different things to different people. For example, a contaminant is defined by the Safe Drinking Water Act (SDWA) as “any physical, chemical, biological, or radiological substance or matter in water” (see *http://www.epw.senate.gov/sdwa.pdf*). This broad definition of contaminant includes every substance that may be found dissolved or suspended in water—everything but the water molecule itself. This is not a very practical definition because this would imply that all water is “contaminated.” Pure water that has nothing dissolved in it does not occur naturally—not even rainfall is pure water, because it contains, at a minimum, some dissolved gases.

The U.S. Environmental Protection Agency defines a contaminant as “Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil” (see *http://epa.gov/region04/superfund/qfinder/glossary.html*). This definition is more practical and allows both manmade constituents and those with geologic sources in water to be defined as contaminants. However, it does not define what “adverse” means, and what may be adverse in one way might be beneficial in another. In this circular, a contaminant is defined as any physical, chemical, biological, or radiological substance or matter in groundwater that is manmade or that impairs the use of water for its intended purpose. Impairment is determined by comparing a measured concentration to benchmarks or guidelines. By this definition, all manmade compounds, such as pesticides and volatile organic compounds, are contaminants because they do not occur naturally in groundwater. If a constituent with a geologic source, such as arsenic, occurs in drinking water at a concentration above its human-health benchmark, it also is considered a contaminant.

Few Manmade Contaminants Were Detected at a Concentration Greater Than a Human-Health Benchmark

Pesticides and volatile organic compounds (VOCs) were detected in shallow groundwater throughout the study area (see chapter 6), but were detected infrequently in drinking-water wells. When these contaminants were detected, the concentrations were less than human-health benchmarks, with the exception of dieldrin. The insecticide dieldrin was detected in one sample from a drinking-water well and in four samples from monitoring wells in an urban area (table 5–1). The concentration in all five samples exceeded the human-health benchmark concentration for dieldrin of 0.002 µg/L. Dieldrin has not been used for more than 25 years, and its occurrence primarily in samples of shallow groundwater in an urban area likely is the result of its use as a termiticide prior to 1987.

Nitrate is one of the most widespread groundwater contaminants in the Nation. However, nitrate was not detected in any sampled drinking-water wells at concentrations greater than the MCL of 10 milligrams per liter as nitrogen (mg/L as N). Nitrate was measured at a concentration greater than the national background concentration of 1 mg/L as N,[11] suggesting inputs related to human sources of nitrogen. Relatively few public-supply wells had nitrate concentrations greater than the background concentration, but almost half of the samples in shallow groundwater in the Memphis urban area had concentrations greater than the background concentration (fig. 5–1).

Pesticides and most VOCs were detected in fewer than 10 percent of samples from drinking-water wells, but several of these contaminants were detected frequently in shallow groundwater overlying the embayment-uplands aquifers in the Memphis area. Two herbicides, atrazine and simazine, and the atrazine degradate, deethylatrazine, were detected in more than half of the samples from the wells in the urban area and were among the most commonly detected herbicides in samples from drinking-water wells (fig. 5–2). Chloroform was among the most frequently detected VOCs in both shallow groundwater and drinking-water wells (fig. 5–3). Chloroform is used in organic synthesis and is a disinfection by-product formed during the chlorination of drinking water and during wastewater treatment.[12] Differences in occurrence of pesticides and VOCs between the shallow monitoring wells and drinking-water wells is in large part a result of differences in shorter groundwater residence times and unconfined conditions for samples of shallow groundwater compared to samples from deeper drinking-water wells. These differences are discussed in more detail in chapters 6 and 7.

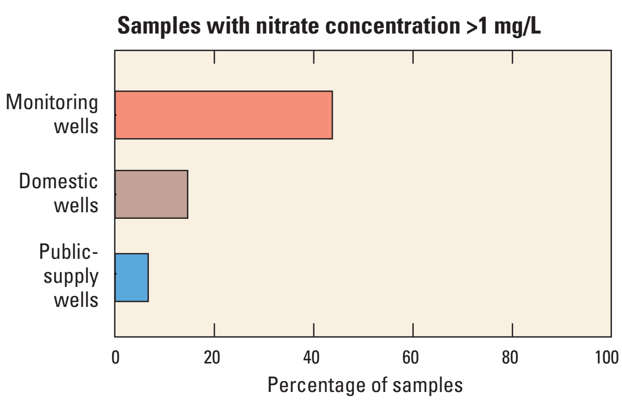


Figure 5–1. Concentrations of nitrate in samples from drinking-water wells generally were less than the national background concentration of 1 mg/L. Almost half of shallow groundwater samples from the urban monitoring wells in the Memphis area had nitrate concentrations above the national background concentration.

A variety of pesticides are used in urban areas to maintain rights-of-way, for control of weeds in lawns and gardens, and termite and other insect control around buildings.

Photograph by Joel Beamer, professional photographer

Some household products contain VOCs or chemicals that can form VOCs in water.

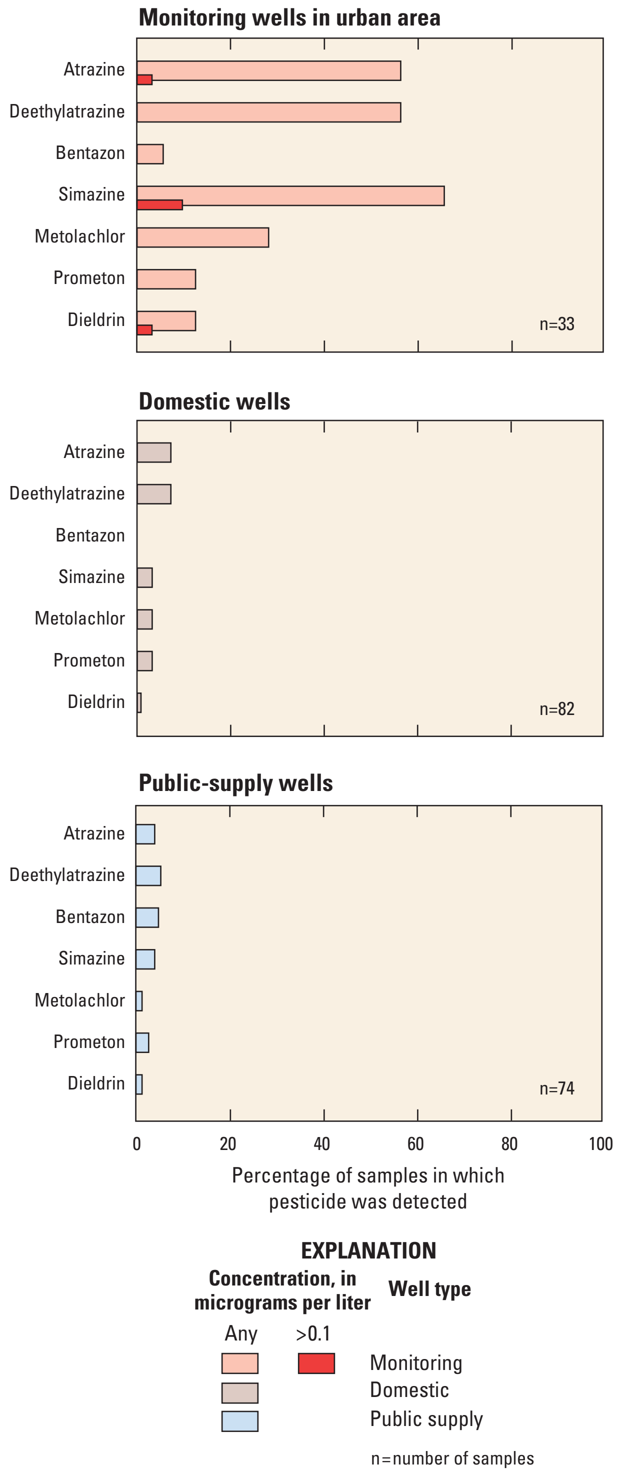


Figure 5–2. Pesticides were detected infrequently in samples from drinking-water wells but were much more commonly detected in samples from shallow monitoring wells in the Memphis urban area because of the shallow depth of these wells and the use of these compounds in areas overlying the aquifer. No pesticides were detected in samples from drinking-water wells at a concentration greater than a common assessment level of 0.1 µg/L.

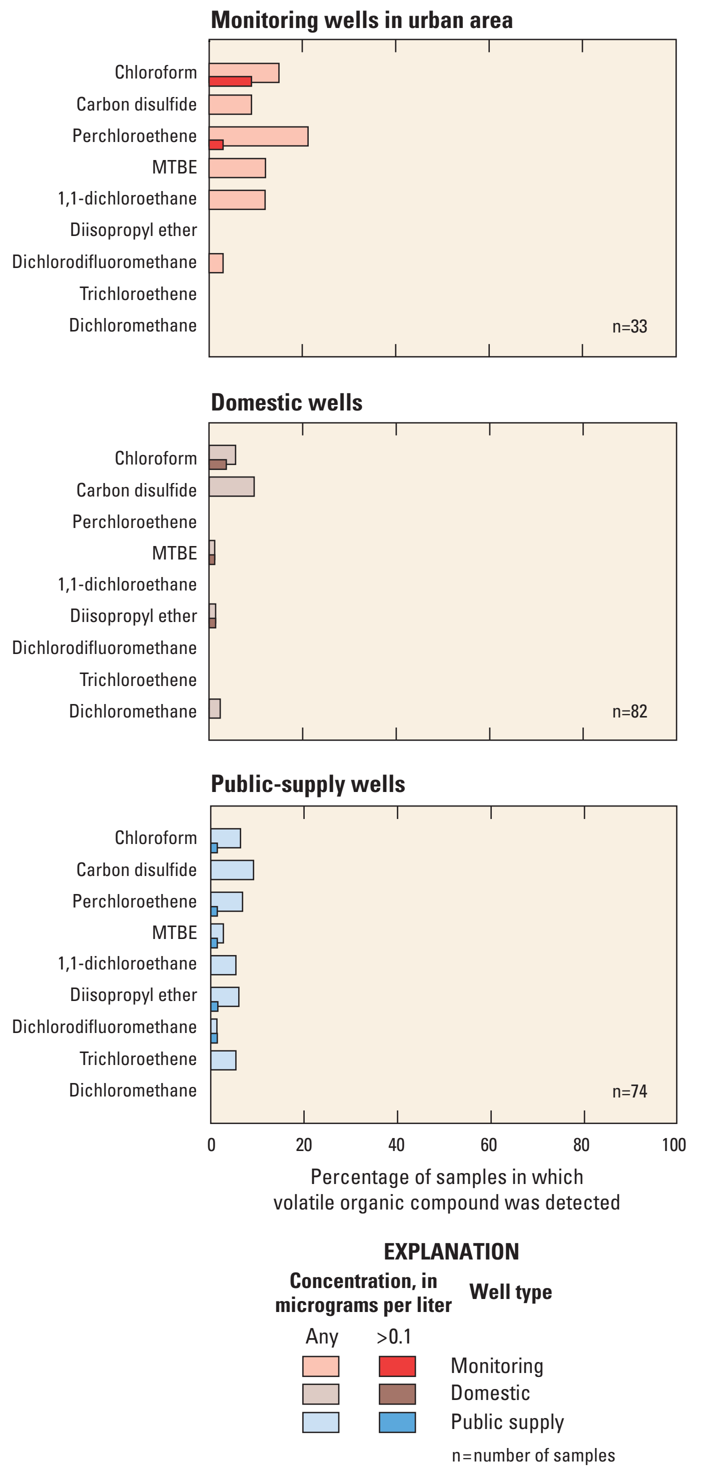


Figure 5–3. No volatile organic compounds were detected in more than 10 percent of samples from drinking-water wells. Chloroform, perchloroethene, methyl *tert*-butyl ether (MTBE), and 1,1-dichloroethane were detected in more than 10 percent of samples from shallow monitoring wells in the Memphis urban area.

Human-health benchmarks and other guidelines used in this assessment

Concentrations of constituents measured for this assessment were compared to human-health benchmarks to place study findings in the context of human health. The benchmarks are threshold concentrations in water above which the concentration of a contaminant in drinking water could adversely affect human health. Human-health benchmarks were available for about two-thirds of the 285 constituents and properties measured for the Principal Aquifer assessments (appendix 3). Two types of human-health benchmarks were used: U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) (*http://water.epa.gov/drink/contaminants/index.cfm*) and U.S. Geological Survey (USGS) Health-Based Screening Levels (HBSLs). MCLs are legally enforceable drinking-water standards that specify the maximum permissible level of a constituent in water that is delivered to any user of a public water system[50] (values used in this report were current as of February 2012). Although MCLs are used to regulate the quality of drinking water only from public-supply sources, they also are useful for evaluating the quality of water from domestic and monitoring wells. An MCL was available for 53 of the constituents measured. For some constituents for which an MCL has not been established, the USGS, in collaboration with the USEPA and others, developed non-enforceable HBSLs by using standard USEPA methods for establishing drinking-water guidelines and current toxicity information[51, 52, 53] (values used in this report were current as of February 2012; see *http://water.usgs.gov/nawqa/HBSL*). An HBSL was available for 135 constituents measured. Radon has neither an MCL nor an HBSL, but two MCLs have been proposed. Copper and lead have USEPA action levels rather than an MCL.

In addition to human-health benchmarks, non-health-based guidelines—Secondary Maximum Contaminant Levels (SMCLs)—were available for some of the constituents measured in this assessment. The SMCLs are non-enforceable guidelines for concentrations of “nuisance” constituents in drinking water that can cause unwanted cosmetic effects, such as skin or tooth discoloration; aesthetic effects, such as unpleasant taste, odor, or color; or technical effects, such as corrosion or sedimentation of plumbing or reduced effectiveness of water treatment.[54]

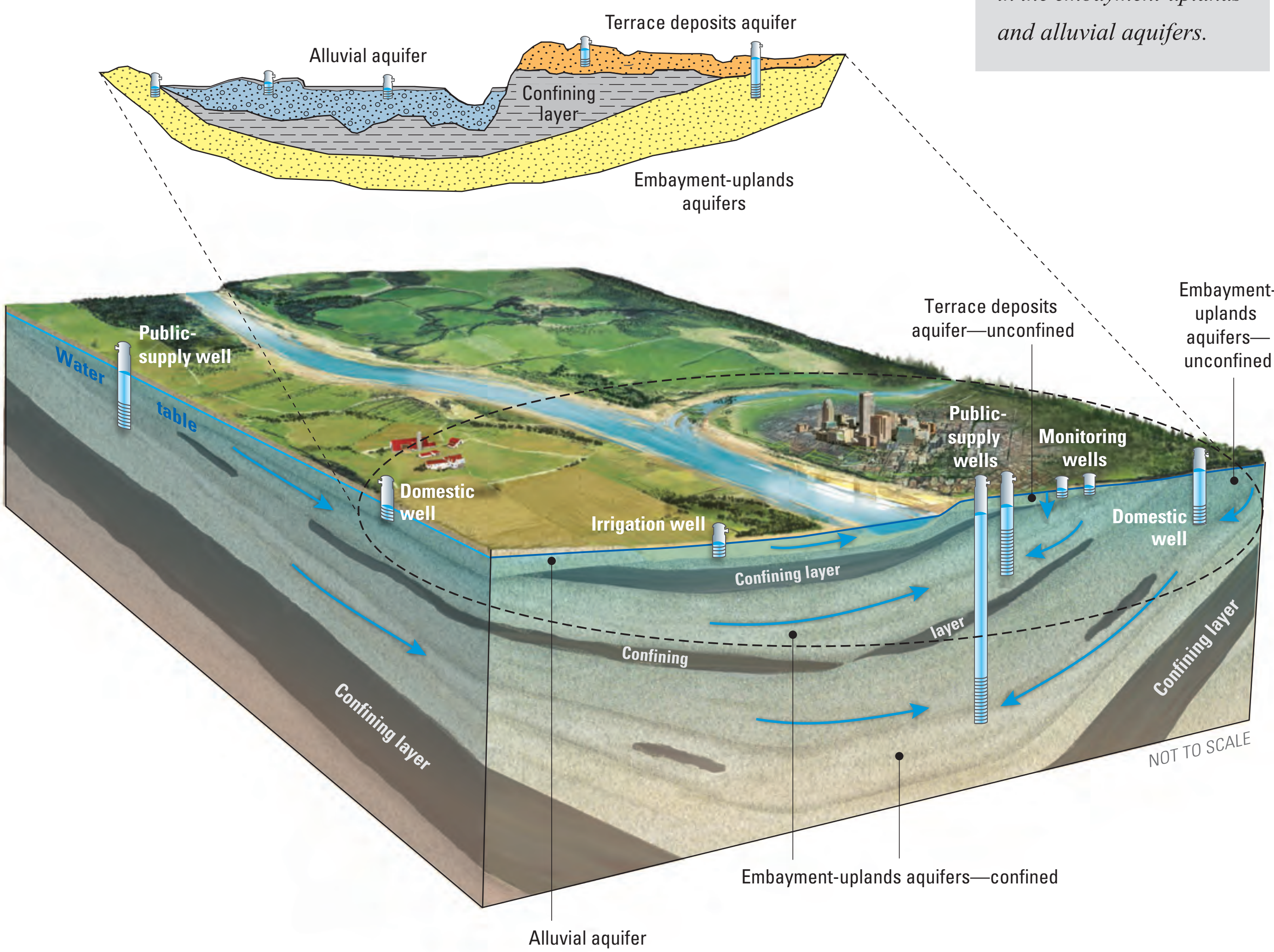
Concentrations greater than one-tenth of a human-health benchmark were used in this assessment to indicate which contaminants occurred, either individually or as mixtures, at concentrations that approach those of potential concern for human health, and to identify contaminants that might warrant additional monitoring and study. The criterion of one-tenth of a benchmark is consistent with various State and Federal practices for reporting contaminant occurrence in groundwater and for identifying contaminants of potential human-health concern (for example, see U.S. Environmental Protection Agency;[49] New Jersey Department of Environmental Protection[60]).

Screening-level assessments, such as this one, provide perspective on the potential relevance of detected contaminants to human health and can help in planning future studies.[52] They are not designed to evaluate specific effects of contaminants on human health and are not a substitute for comprehensive risk assessments. It is important to note that occurrence of a contaminant at a concentration greater than its benchmark does not mean that adverse effects are certain to occur, because the benchmarks are conservative (protective) and source-water samples were collected prior to any treatment or blending that could alter contaminant concentrations in finished drinking water. There are water-treatment options, such as charcoal filtration, that can be used to lower the concentration of the contaminant to below the benchmark before the water is consumed.

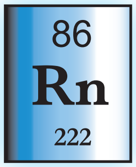
Chapter 6: *Understanding Where and Why Key Contaminants Occur in Shallow Groundwater*

Shallow groundwater from the embayment-uplands and alluvial aquifers is the primary source of drinking water in rural parts of the study area. The alluvial aquifer also is an important source of water for irrigation of crops. Characterizing shallow groundwater quality and whether it is changing through time is important for the continued use of this resource. Because shallow groundwater can move to deeper parts of these aquifers, which is where most public water-supply wells are screened, the quality of shallow groundwater can affect the quality and use of deeper groundwater resources.

This chapter describes the sources of and factors that affect radon, manganese, arsenic, chloride, phosphorus, nitrate, pesticides, and VOCs in shallow (≤200 feet) groundwater in the embayment-uplands and alluvial aquifers.



Radon



Radon is an element that results from the radioactive decay of uranium in aquifer materials. Radon in drinking water is associated with lung cancer and stomach cancer.

Radon was detected at concentrations greater than the proposed MCL of 300 pCi/L in more than one-fourth of the samples of shallow groundwater, but it was not detected at a concentration greater than the proposed alternative MCL of 4,000 pCi/L in any samples.

Radon (radon-222), a radioactive gas that is part of the decay series of uranium, occurs naturally in aquifer sediments and rocks. Radon emits radiation, and inhalation of excessive amounts of radon can cause cancer. In households that use groundwater for water supply, radon can be released from the water into the air during showers and other uses. Radon in water is of greatest concern in closed water-supply systems with short retention times, such as domestic wells. In this type of system, radon may not escape from the water before the point of use, and water moves to the tap from the aquifer more quickly than the half-life of radon, which is 3.8 days.

Elevated concentrations were most common in samples from the embayment-uplands aquifers, where more than half of the samples had concentrations greater than 300 pCi/L (fig. 6–1). However, samples from shallow depths in the embayment-uplands aquifers were collected only in a subset of wells in Louisiana and Texas, and these results may not be representative of the entire aquifer system. The maximum measured radon concentration was 2,200 pCi/L, which is about half of the proposed alternative MCL of 4,000 pCi/L. Elevated radon concentrations are associated with heavy mineral deposits in the sediments that make up the embayment-uplands aquifers.

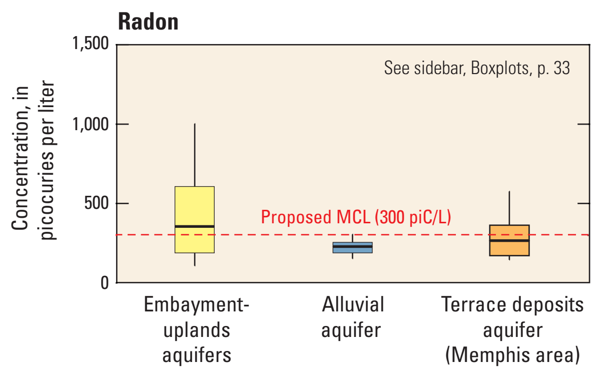
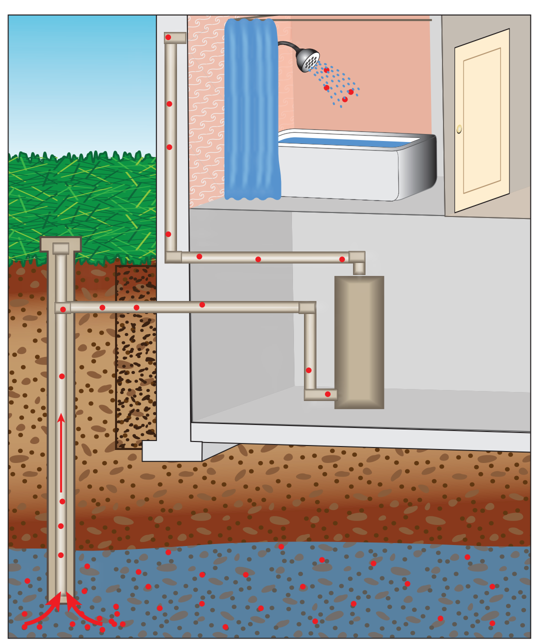


Figure 6–1. Concentrations of radon were greater than the proposed MCL of 300 pCi/L in more than half of the samples of shallow groundwater from the embayment-uplands aquifers. No sample from any aquifer contained radon at a concentration that exceeded the alternative MCL of 4,000 pCi/L.



Radon gas (represented by red dots) dissolved in groundwater can move with water from a domestic well into a household's plumbing. When the water is aerated at faucets, radon can be released into the air and inhaled while people shower or drink from faucets.

Modified from Otton and others[13]

Manganese

Manganese is a trace element found in aquifer materials and some industrial wastes. Manganese has a human-health benchmark of 300 µg/L because of neurological effects.

Manganese is a potential human-health concern for those who rely on untreated water from domestic wells for their drinking water, especially if those wells tap the alluvial aquifer, where the groundwater is almost always anoxic. Under anoxic conditions, oxide coatings on aquifer sediments dissolve and release manganese.

Manganese concentrations exceeded the human-health benchmark concentration of 300 µg/L in about 38 percent of the shallow groundwater samples. Most (80 percent) of these elevated concentrations were in samples from the alluvial aquifer (fig. 6–2). Elevated concentrations of manganese in drinking water are a human-health concern because of potential effects to neurological function.[14]

Manganese is commonly present in sediments and rocks at trace amounts but remains bound to sediments under oxic conditions. Under anoxic conditions, oxide coatings and minerals on aquifer sediments dissolve and release manganese, which is soluble under these conditions.

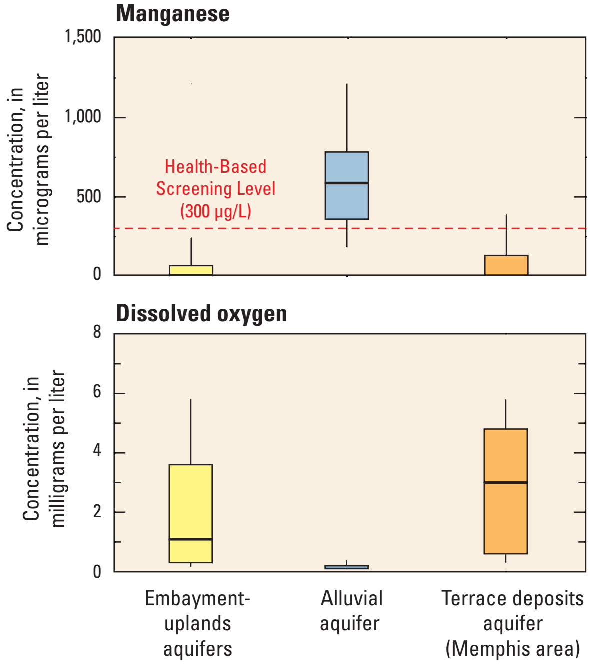


Figure 6–2. Elevated concentrations of manganese were measured primarily in samples from the alluvial aquifer, where nearly all samples had concentrations greater than the human-health benchmark of 300 µg/L and nearly all were anoxic. Higher concentrations of dissolved oxygen in the embayment-uplands aquifers and terrace deposits resulted in lower concentrations of manganese than in the alluvial aquifer.

Nearly all of the wells sampled in the alluvial aquifer had concentrations of manganese that exceeded the human-health benchmark of 300 µg/L.

Chapter 6

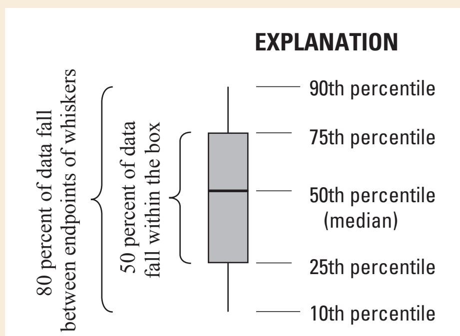
Boxplots

Boxplots are used to illustrate how results are distributed within a group. The "box" ranges from the 25th to the 75th percentile and represents 50 percent of the data. The horizontal line in the middle of the box is the median value—one-half of the values in the group are greater than the median and one-half are less.

Percentiles describe the percentage of values in a group that are less than the given value: 25 percent of the values in a group are less than the 25th percentile; 75 percent of the values in a group are less than the 75th percentile. The median is also the 50th percentile.

If, for example, the 75th percentile for the measured concentration of a contaminant in a group of wells is equal to the human-health benchmark for that contaminant, then 75 percent, or three-fourths, of the wells have a concentration of that contaminant less than the benchmark, and 25 percent, or one-fourth, have a concentration greater than the benchmark.

The "whiskers" (vertical lines) in these figures extend to the 10th and 90th percentiles; box and whiskers together represent 80 percent of the data.



33
As
75

Arsenic is a trace element found in aquifer materials and can also come from pesticide application or industrial waste. Long-term exposure to arsenic in drinking water is related to elevated risks of cancer and skin damage.

Arsenic

Arsenic in groundwater is a potential human-health concern for those who rely on untreated domestic wells for their drinking water, especially if those wells tap the alluvial aquifer. One in 10 samples from the alluvial aquifer had concentrations of arsenic that exceeded the MCL of 10 µg/L. Anoxic conditions in the alluvial aquifer promote the release of arsenic from the aquifer sediments.

Arsenic in drinking water is a concern because it affects human health in a number of ways, including contributing to the development of several types of cancer.[15] Arsenic concentrations exceeded the MCL in about 10 percent of the samples from the alluvial aquifer and were greater than one-tenth of the MCL (1 µg/L) in about 60 percent of the samples. In contrast, only 2 percent of samples from wells in the shallow parts of the embayment-uplands aquifers contained arsenic at a concentration that exceeded the MCL, and concentrations greater than 1 µg/L were predominantly from wells in Texas (fig. 6–3). Concentrations of arsenic did not exceed the MCL in any of the samples from monitoring wells in the Memphis area.

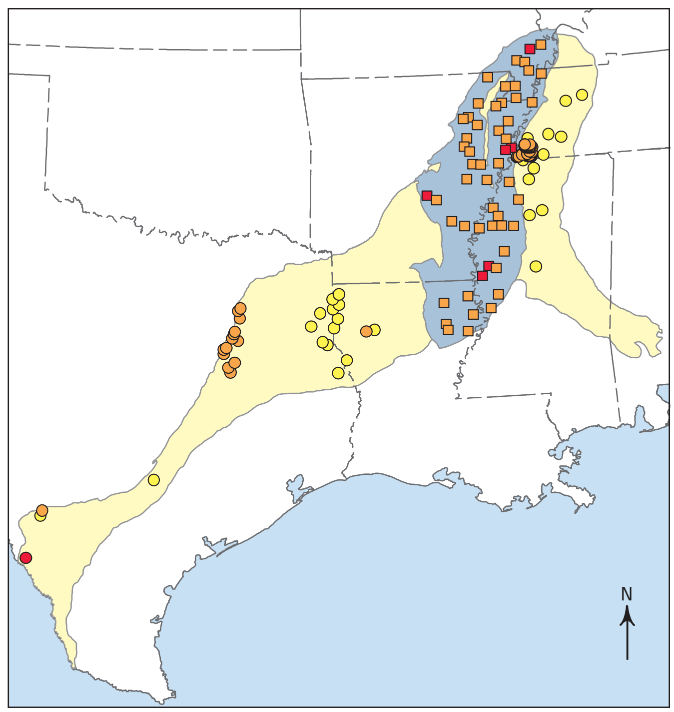


Figure 6–3. Arsenic was detected at concentrations greater than the MCL primarily in samples from the alluvial aquifer. Arsenic adheres to iron oxides that coat the alluvial aquifer sediments and can be released into groundwater under low dissolved-oxygen conditions, which cause the iron oxide coatings to dissolve.

EXPLANATION

Embayment-uplands aquifers

Alluvial aquifer

Arsenic concentration, in micrograms per liter

<1

1 to 10

>10

The source of arsenic in groundwater in the alluvial aquifer likely is the aquifer sediments.[16, 17] Arsenic and other trace elements often are bound to iron oxide coatings on aquifer sediments. Under anoxic conditions, these iron oxides dissolve, releasing iron and arsenic into the groundwater. Correlations between concentrations of arsenic and iron (fig. 6–4) and other constituents (calcium, bicarbonate, and molybdenum) that are contributed to groundwater primarily from geologic sources indicate aquifer sediments are the predominant source of arsenic. The association between elevated arsenic and iron concentrations is consistent with results from a local study of the alluvial aquifer in which arsenic was detected at concentrations exceeding the MCL in about 20 percent of samples and its occurrence was attributed to dissolution of iron oxide coatings on aquifer sediments.[18] Because drinking water from domestic wells typically is untreated and not monitored routinely, arsenic is a potential human-health concern for rural households with wells in the alluvial aquifer. Iron stains on plumbing fixtures in households that use water from a domestic well could be an indication that arsenic concentrations are elevated because of the association of high arsenic and iron concentrations.

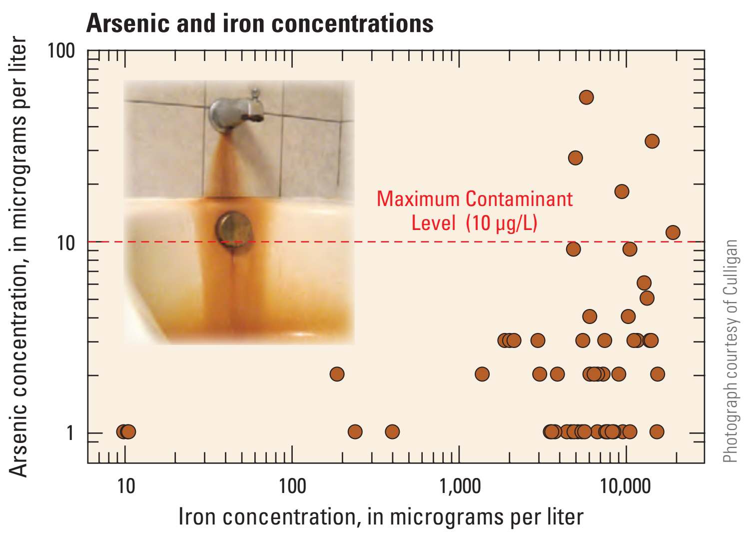
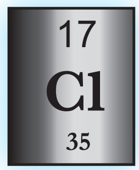


Figure 6–4. Elevated concentrations of arsenic were associated with high concentrations of iron in the alluvial aquifer. Iron stains on plumbing fixtures indicate that households using domestic wells in the alluvial aquifer might have elevated concentrations of arsenic in their water.



Chlorine is present in minerals as chloride—a familiar example is halite (sodium chloride), which is used as table salt. Chloride typically is present in very small amounts in most aquifer materials. Runoff from roads that have been treated with road salt, agricultural drainage, and saltwater encroachment all can cause elevated concentrations of chloride in groundwater.

Chloride

Chloride concentrations were less than the SMCL of 250 mg/L in most samples of shallow groundwater. However, elevated concentrations of chloride detected in some parts of the embayment-uplands aquifers and alluvial aquifer could limit the use of shallow groundwater as a source of water for domestic supply and irrigation.

Elevated concentrations of chloride in shallow groundwater can affect the suitability of that water for irrigation and drinking. High concentrations of chloride in irrigation water can adversely affect rice and soybean production by contributing to increased soil salinity. Rice is particularly sensitive to chloride, and use of groundwater with concentrations greater than 100 mg/L is not recommended for irrigation.(19) Although these levels are not a concern for human health, chloride concentrations greater than the USEPA's SMCL of 250 mg/L can impair the taste of water and necessitate water treatment or increase treatment costs.

Concentrations of chloride greater than 100 mg/L were measured in about 8 percent of shallow groundwater samples (fig. 6–5). In shallow parts of the embayment-uplands aquifers, chloride concentrations tended to be higher in samples collected west of the Mississippi River than in samples collected east of the river. Higher concentrations west of the river are caused by differences in climate and recharge rates. Average annual recharge in the southwestern part of the study area is 2.2 inches per year, but east of the Mississippi River, average annual recharge is 11 inches per year.(20) Additionally, concentrations of chloride are higher in rainfall in the southwest part of the study area (as much as 0.8 mg/L) than in rainfall east of the Mississippi River (0.1–0.3 mg/L). The combination of lower recharge rates and higher chloride concentrations in rainfall results in higher chloride concentrations in shallow groundwater from evaporation of atmospheric deposition. Locally, elevated concentrations of chloride also can be associated with manmade sources of chloride, such as road salt, potassium chloride (potash) applied to cultivated fields, oil field brines, and leaking septic systems.

Chloride in irrigation water contributes to elevated soil salinity, which negatively affects rice and soybean production.

Concentrations of chloride in shallow groundwater exceeded the chloride SMCL infrequently, but local studies in southeastern Arkansas have identified areas in the alluvial aquifer where concentrations of chloride exceeded 1,000 mg/L(21) and have negatively affected rice and soybean production.(22) Elevated concentrations of chloride are associated with areas overlain by backswamp deposits of alluvium, which consist primarily of fine-grained, clay-rich sediments. In areas of backswamp deposits, recharge is limited and evapotranspiration rates are high, resulting in increased salinity in the subsurface. Historical data for samples collected in this area indicate that concentrations of chloride have been high since the 1950s and are not increasing over time.(21) The spatial distribution of elevated chloride concentrations (fig. 6–5 inset) and the lack of changes in concentration over time indicate that the source of chloride is not related to the overlying agricultural land use but instead occurs naturally. Upward movement of brackish water along faults from deeper zones might be another source of chloride in southeastern Arkansas that could contribute to elevated concentrations.(21)

Cultivation of rice, an important crop in the study area, requires large amounts of irrigation water from the alluvial aquifer. The high chloride concentrations in groundwater in parts of this aquifer may limit groundwater use for irrigation or necessitate use of deeper aquifers as a suitable source of water.

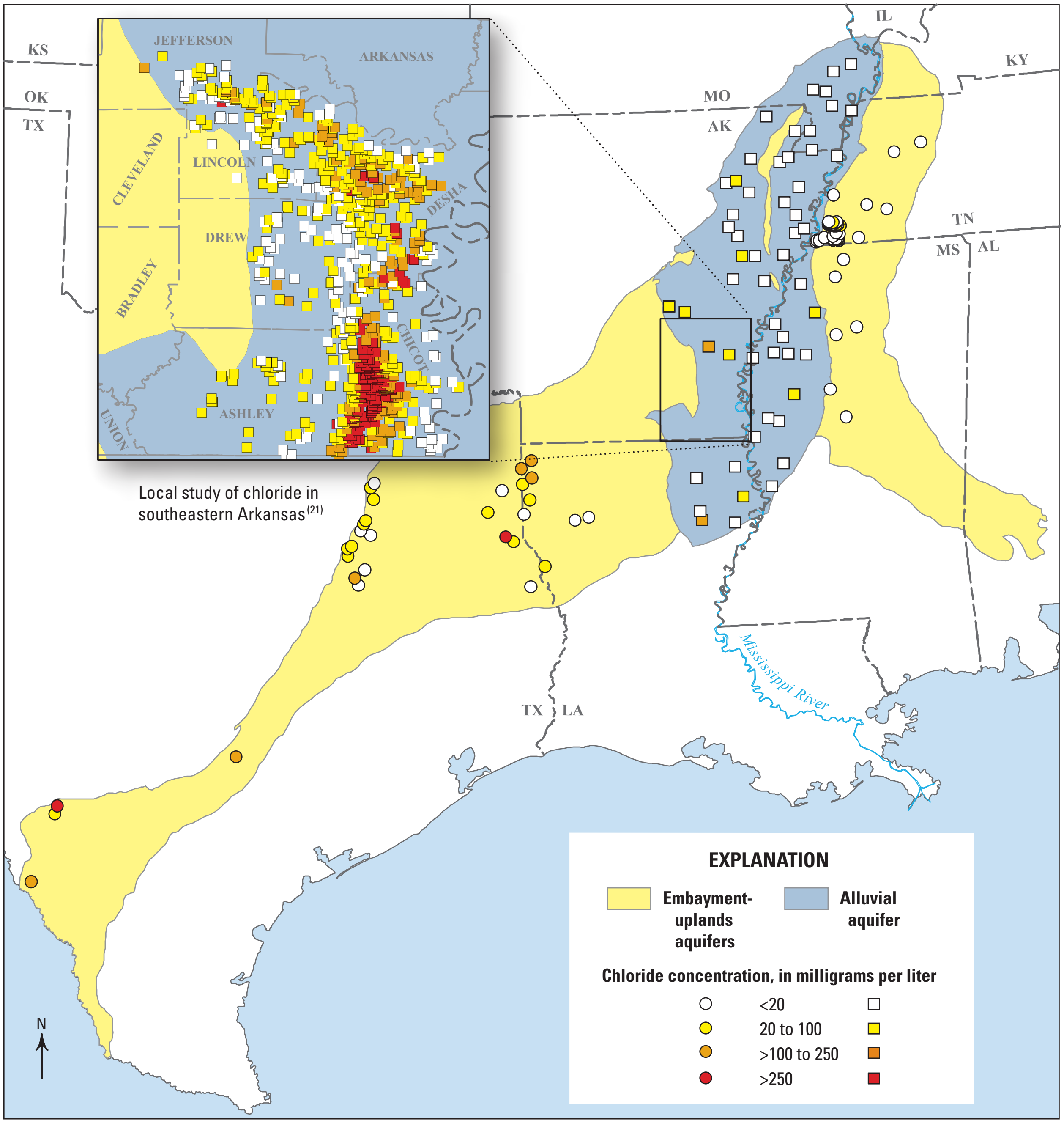
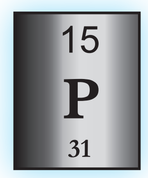


Figure 6–5. Chloride concentrations measured in most samples for this assessment were less than the SMCL for drinking water (250 mg/L) and the recommended irrigation water limit for rice (100 mg/L). However, groundwater in the alluvial aquifer in southeastern Arkansas (see inset) had elevated concentrations of chloride. These areas coincide with areas of fine-grained sediments in the upper part of the Mississippi River Valley alluvium that limit recharge and concentrate chloride through evapotranspiration.



The element phosphorus is an essential nutrient for plant and animal growth. Phosphorus tends to bind to soils, so concentrations of phosphorus in groundwater generally are low.

Phosphorus

Elevated phosphorus concentrations in streams, lakes, and reservoirs can lead to excessive algal growth, decreased oxygen levels, fish kills, and increased water-treatment costs. Groundwater discharge makes up much of the streamflow during low-flow conditions. Elevated concentrations of phosphorus in shallow groundwater may contribute to nutrient enrichment of the receiving streams. Understanding the potential contribution of phosphorus from the alluvial aquifer to streams in the lower Mississippi watershed is critical to the development of effective nutrient management strategies.

Groundwater generally is not considered an important source of phosphorus to streams because concentrations in groundwater typically are much lower than levels of concern for streams and lakes. Concentrations of dissolved phosphorus in groundwater in most aquifers are low because phosphorus that is not taken up by plants tends to adhere to soil and aquifer sediments and is not readily transported in groundwater.[23] Concentrations of phosphorus in

Concentrations of phosphorus in the alluvial aquifer were among the highest in groundwater across the Nation and often exceeded the recommended Ecoregion criterion for total phosphorus in streams.

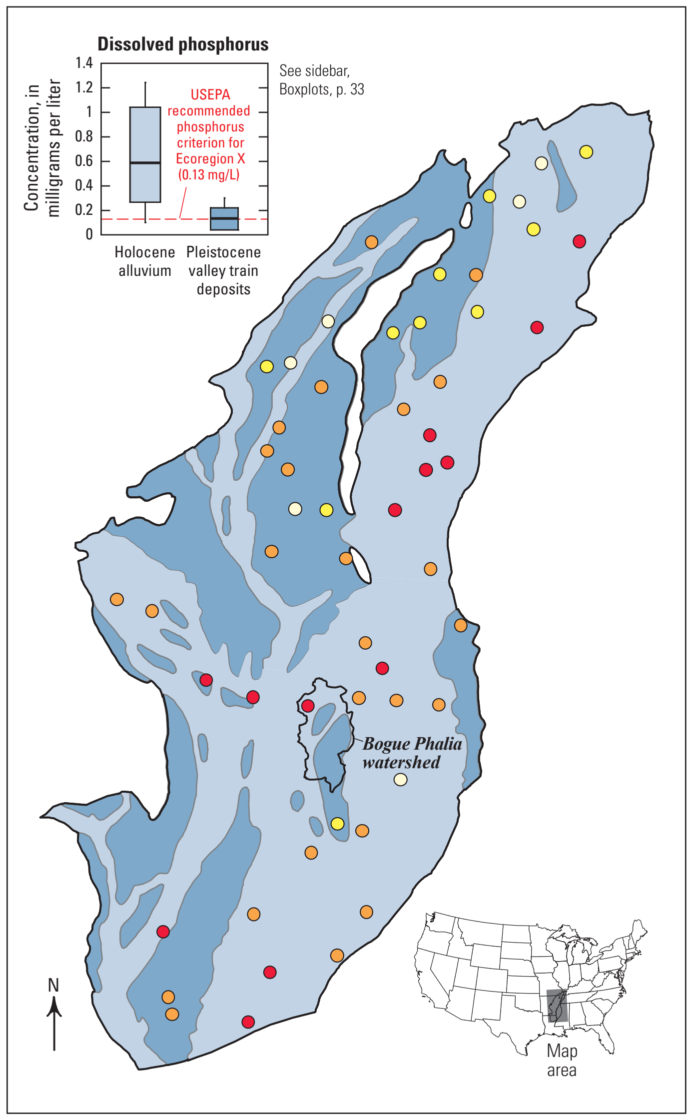


Figure 6–6. Phosphorus concentrations greater than the recommended criteria of 0.13 mg/L for total phosphorus for streams in Ecoregion X were widespread in the alluvial aquifer. These elevated concentrations in groundwater could impair streamwater quality, especially during periods of low flow when groundwater discharge and irrigation return flows make up all of the streamflow.

EXPLANATION

Subunits of the alluvial aquifer

Holocene alluvium

Pleistocene valley train deposits

Phosphorus concentration, in milligrams per liter

<0.03

0.03 to 0.13

>0.13 to 0.60

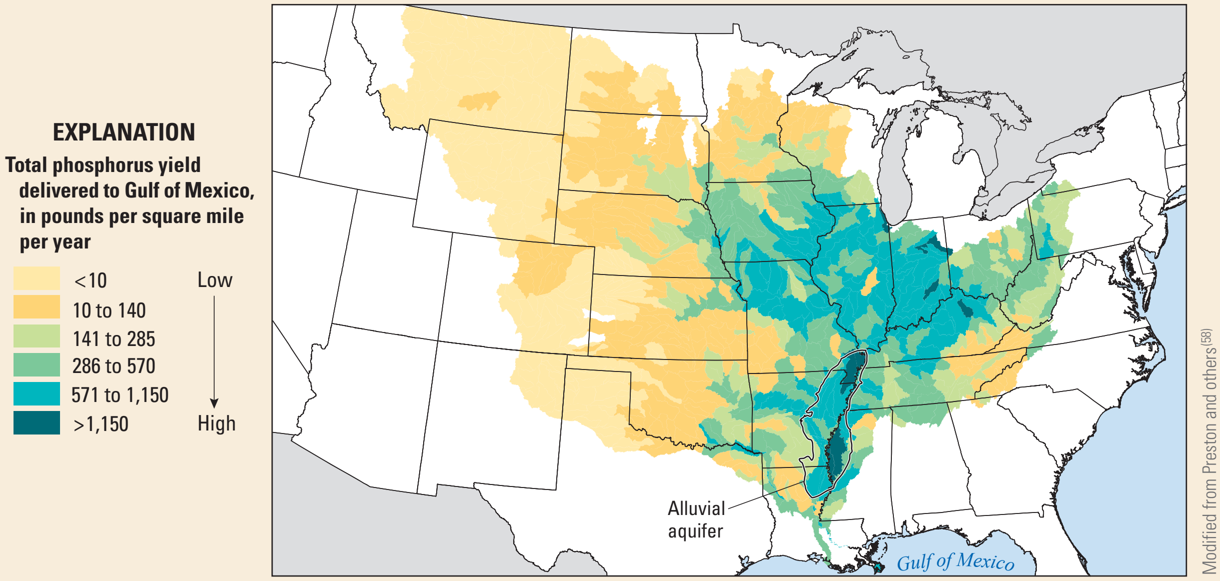
>0.60

samples from the alluvial aquifer (fig. 6–6) are higher than concentrations commonly found in groundwater and could be a source of phosphorus to streams in the lower Mississippi watershed.[24] During low-flow conditions, when streamflow is predominantly made up of groundwater discharge, groundwater with elevated concentrations of phosphorus can contribute to nutrient enrichment of the receiving streams.

Concentrations of phosphorus in samples from the alluvial aquifer were among the highest in the Nation (appendix 4). The median concentration of phosphorus in samples from the alluvial aquifer was almost 10 times greater than the national background concentration of 0.03 mg/L as phosphorus.[11] The highest concentrations of phosphorus were measured in wells in the Holocene alluvium, one of two subunits that make up the alluvial aquifer (fig. 6–6). The median concentrations for both subunits of the alluvial aquifer were greater than the USEPA recommended criterion of 0.13 mg/L for total phosphorus in streams for Ecoregion X.[25] Phosphorus concentrations also were elevated in parts of the embayment-uplands aquifers—the median concentration of 0.07 mg/L is about twice the background concentration. In contrast, the median concentration of <0.01 mg/L in samples from the terrace deposits is more typical of phosphorus concentrations in groundwater throughout much of the Nation.[11]

Elevated concentrations of nutrients in groundwater can impair surface-water quality

A hypoxic zone, an area where oxygen levels drop too low to support most life in bottom and near-bottom waters, forms each year off the coast of Louisiana in the Gulf of Mexico. The Gulf of Mexico hypoxic zone has ranged in size from about 2,800 to 8,000 square miles over the last 5 years. The size of the seasonal hypoxic zone is related to the amounts of nitrogen and phosphorus entering the Gulf from the Mississippi and Atchafalaya Rivers.[55, 56, 57] Streams overlying the alluvial aquifer are among those that deliver the largest yields of phosphorus to the Gulf. Shallow groundwater with elevated concentrations of phosphorus in the alluvial aquifer could be contributing to the elevated phosphorus yields, especially during periods of low streamflow. Understanding the potential contribution of phosphorus from groundwater to streams is critical for the development of effective nutrient reduction strategies.



Watersheds contributing phosphorus to the Gulf of Mexico.

Phosphorus can be released from aquifer sediments into groundwater

Elevated concentrations of phosphorus were related to anoxic conditions in the aquifer and concentrations of dissolved iron. Under anoxic conditions, iron oxides that coat aquifer sediments dissolve, releasing the bound phosphorus into the groundwater. Water in the alluvial aquifer becomes increasingly reduced with depth below the water table.(26) An increase in phosphorus concentrations with depth and the association between elevated concentrations of phosphorus and iron indicate that the predominant source of phosphorus in the alluvial aquifer is phosphorus bound to iron oxides on the aquifer sediments.

Groundwater seeps along streams overlying the alluvial aquifer are stained red from iron that precipitates when the anoxic groundwater is exposed to oxygen in the atmosphere. Dissolved phosphorus in groundwater likely is associated with this iron and could contribute to the instream phosphorus loads.

Groundwater contribution of phosphorus to the Bogue Phalia watershed

Groundwater discharge makes up most of the flow in streams during low-flow conditions. In agricultural settings in the study area, irrigation return flows also contribute to streamflow throughout the growing season (May to August). Together, these control streamwater quality during the summer months.

The estimated groundwater contribution of phosphorus in the Bogue Phalia watershed in west Mississippi was less than 10 percent of the total phosphorus load. During low-flow conditions, however, the amount of phosphorus from groundwater was as much as 25 percent of the total phosphorus load (fig. 6–7). A better understanding of the fate of phosphorus in groundwater that discharges to streams and from irrigation return flows is needed to provide resource managers with information to account for the groundwater contribution of phosphorus. The amount of the phosphorus load in the Bogue Phalia watershed contributed by groundwater was estimated by assuming that the dissolved phosphorus load during low-flow conditions represented the groundwater contribution to the total phosphorus load.(24) This analysis provides an initial estimate of the contribution of phosphorus from groundwater to streams in the study area.

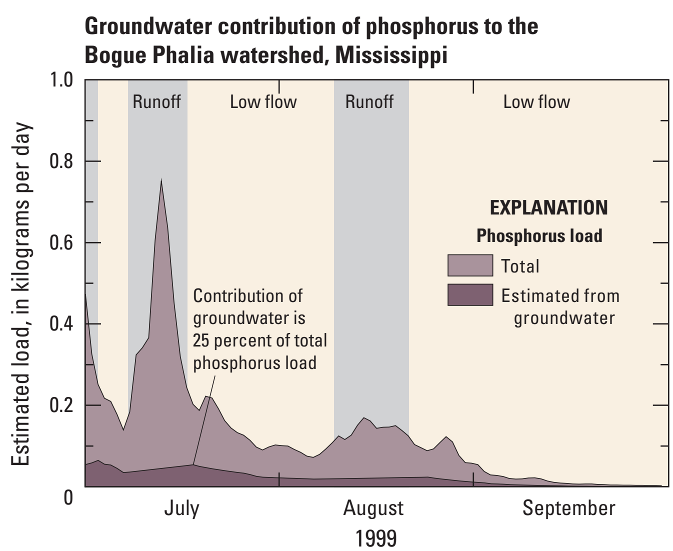


Figure 6–7. During low-flow conditions, the contribution of phosphorus from groundwater may account for as much as 25 percent of the total phosphorus load in the Bogue Phalia watershed. Understanding the potential role of groundwater as a source of phosphorus to streams is critical to the development of nutrient management strategies in the area.

Nitrate

Although the lower Mississippi River Valley is a major agricultural region, nitrate in shallow groundwater is not a widespread issue because of comparatively slow infiltration rates and anoxic conditions in many parts of the study area.

Despite widespread use of nitrogen-containing fertilizer, concentrations of nitrate in shallow groundwater were low (fig. 6–8), typically less than 1 mg/L as N, a threshold that commonly is used to indicate input of nitrogen from human activities.[11] Nitrate was not detected in 70 percent of samples from the alluvial aquifer. The surprisingly infrequent detection of nitrate in samples from the alluvial aquifer highlights how important natural geochemistry is in controlling nitrate occurrence.

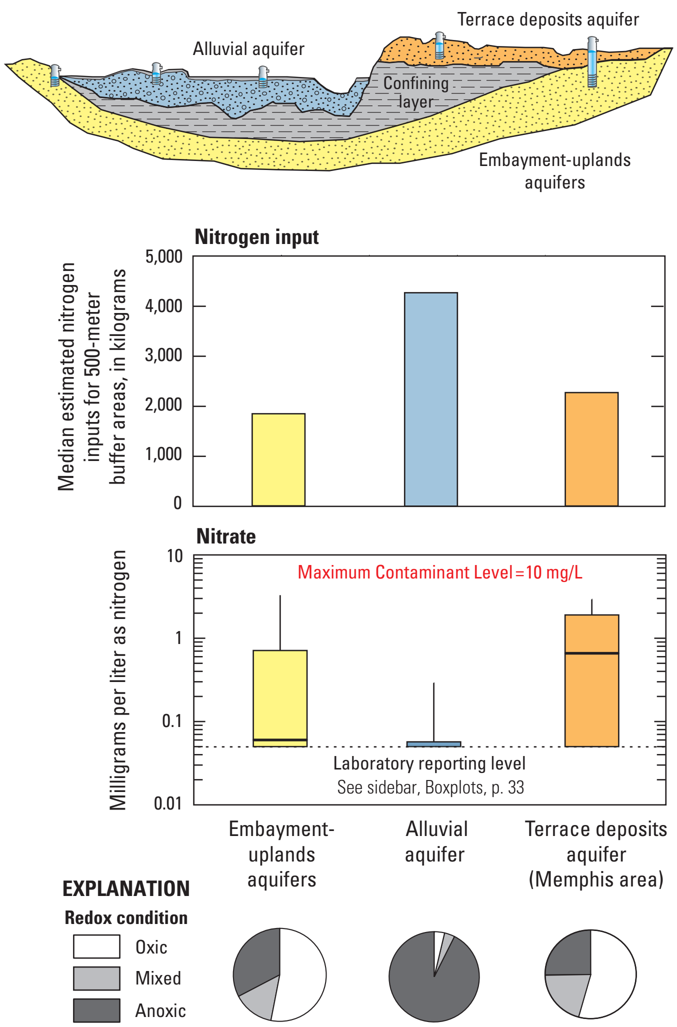


Figure 6–8. Despite the application of large amounts of fertilizers in areas overlying the alluvial aquifer, concentrations of nitrate in groundwater are low because of low rates of recharge and anoxic conditions in the aquifer that promote denitrification.

Although more than twice the amount of nitrogen is applied in areas overlying the alluvial aquifer than in areas overlying the embayment-uplands aquifers, concentrations of nitrate in samples of shallow groundwater from the alluvial aquifer were much lower than those from the embayment-uplands aquifers and terrace deposits. The difference is because groundwater in the alluvial aquifer is almost always mildly to strongly reducing (see sidebar, How do redox reactions work? p. 24). Under these reducing conditions, nitrate is converted to nitrogen gas through denitrification, leading to nitrate concentrations in the alluvial aquifer that are lower than expected given the relatively high nitrogen inputs to areas overlying this aquifer (fig. 6–9) (see sidebar, Nitrate concentrations in the alluvial aquifer were lower than in other aquifers across the Nation, p. 43).

Redox conditions in the shallow and unconfined parts of the embayment-uplands aquifers are typically oxic, and nitrate concentrations are greater than 1 mg/L as N in some areas of the embayment-uplands aquifers (fig. 6–8). Nitrate concentrations were highest in shallow groundwater in the terrace deposits in the Memphis area. These relatively high concentrations, as compared to concentrations in samples from other aquifers in the embayment-uplands aquifers, are likely because of the shallow depth of wells and predominantly oxic conditions in many parts of the terrace deposits aquifer in the Memphis area.[17]

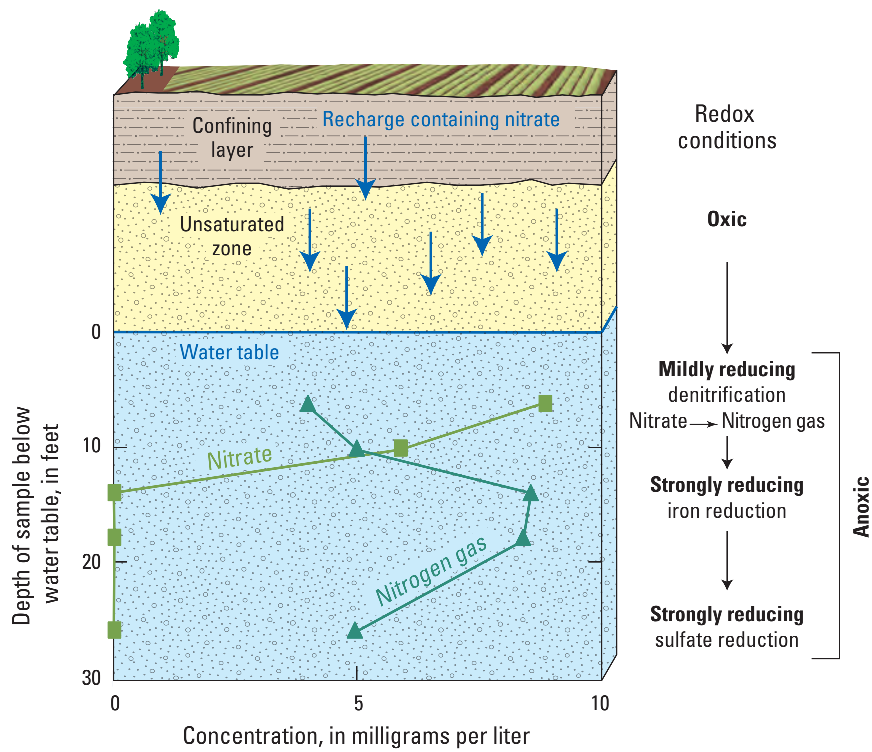
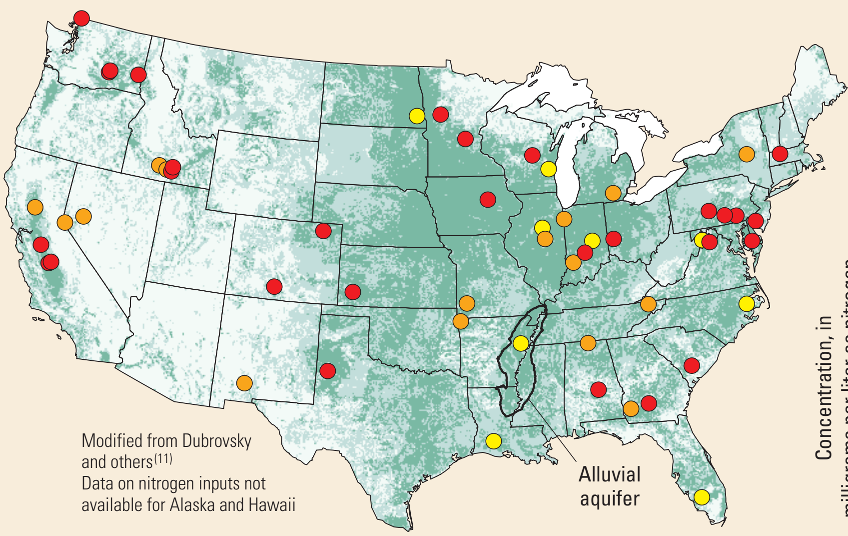


Figure 6–9. Concentrations of nitrate were highest just below the water table in the alluvial aquifer. As redox conditions change from oxic to anoxic with increasing depth, nitrate is converted to nitrogen gas through denitrification. As a result, concentrations of nitrate are low in the deeper parts of the aquifer, which are used for irrigation and drinking water.

Nitrate concentrations in the alluvial aquifer were lower than in other aquifers across the Nation

Compared to many aquifers across the Nation, nitrate concentrations in the alluvial aquifer were low (appendix 4), even though annual nitrogen inputs in largely agricultural counties were as much as 26,000 pounds per square mile. The primary nonpoint sources of nitrogen that contribute to nitrate in groundwater include agricultural fertilizer application, confined and unconfined livestock operations, and atmospheric deposition. Nitrogen inputs in areas overlying the alluvial aquifer were comparable to inputs in the upper Mississippi River Basin, for example, in Illinois, Iowa, Indiana, and Ohio. However, the hydrogeology and anoxic conditions in the aquifer that facilitate denitrification result in concentrations of nitrate in groundwater that are hundreds of times lower than in many agricultural areas across the Nation.



EXPLANATION

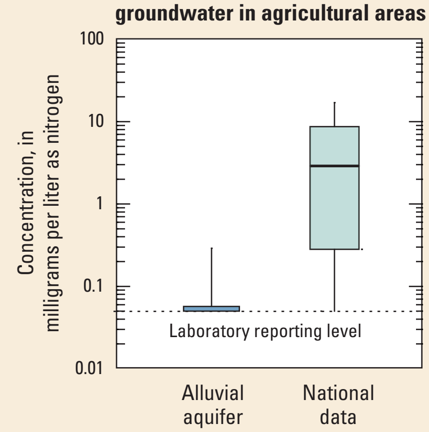
Estimated 1997 nitrogen inputs from fertilizer, manure, and atmosphere, in pounds per square mile

- <2,900
- 2,900 to 15,000
- >15,000

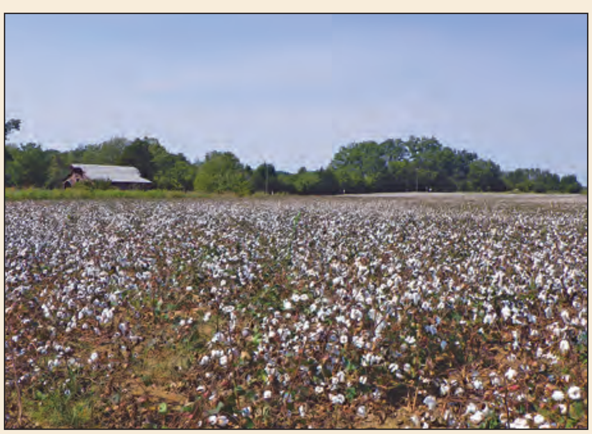
Median concentration of nitrate in shallow groundwater in agricultural areas, in milligrams per liter as nitrogen

- Low (<0.08)
- Medium (0.08 to 2.6)
- High (>2.6)

Nitrate concentration in shallow groundwater in agricultural areas



See sidebar, Boxplots, p. 33



Nitrate concentrations in shallow groundwater in the Memphis area have increased over time

Contamination of groundwater in the shallow aquifers is a concern in the Memphis area because of the potential for shallow groundwater to move downward and adversely affect the quality of the drinking-water supply.[9, 27] Sources of nitrate in urban settings include leaking sewers or septic systems, lawn fertilizers, atmospheric deposition, and point sources such as landfills. Nitrate concentrations in shallow groundwater in the Memphis area were less than the MCL of 10 mg/L as N, but concentrations have increased over time in monitoring wells that were sampled in 1997 and 2006.

More than half of the samples collected in 2006 had concentrations higher than the samples collected from the same wells in 1997 (fig. 6–10), and the median concentration of nitrate increased from 0.5 to 1.3 mg/L as N. Results for a subset of wells with four additional samples collected from 2002 to 2009 demonstrate that nitrate concentrations both increased and decreased during the time samples were collected (fig. 6–11). An inverse relation between changes in water levels and nitrate concentrations at one of these wells indicates that hydrologic factors, such as changes in the amount of recharge, likely account for some of the change in concentration through time. A higher concentration of nitrate in 2009 than in 2002, when water levels were comparable, indicates an increase over time related to nitrogen inputs associated with the overlying urban land use. Changes in concentrations of nitrate in groundwater may lag several years to decades behind changes in the amount of nitrogen input at land surface because of the length of time it takes water and contaminants to move through an aquifer.[11, 28] The median age of shallow groundwater in the Memphis area was about 20 years,[29] and a similar lag time likely exists between changes in land use—such as urbanization—and a change in the occurrence of nitrate in shallow groundwater. The areas in which most of these wells are located had been developed for 20 or more years when samples were collected in 2006, so much of the observed increase in nitrate concentrations likely is related to sources associated with urban land use. Long-term hydrologic and water-quality data are needed to understand the factors that affect concentrations of nitrate and other contaminants in shallow groundwater that are related to human activities.

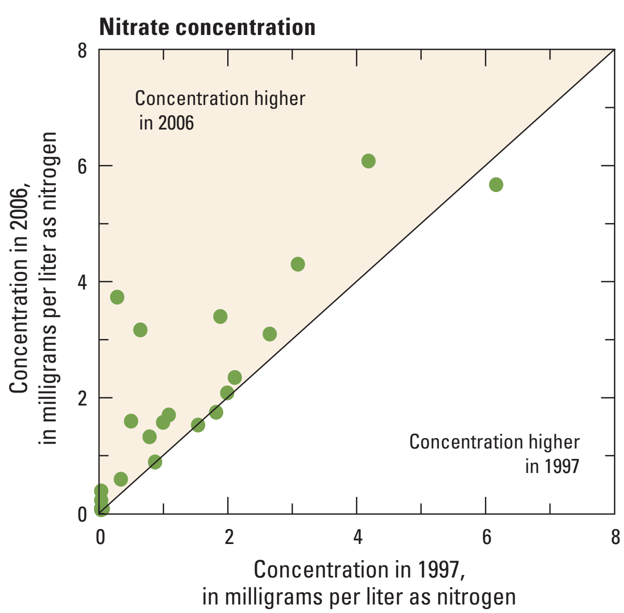


Figure 6–10. Nitrate concentrations in shallow groundwater were higher in 2006 than in 1997 for most of the monitoring wells in the Memphis area.

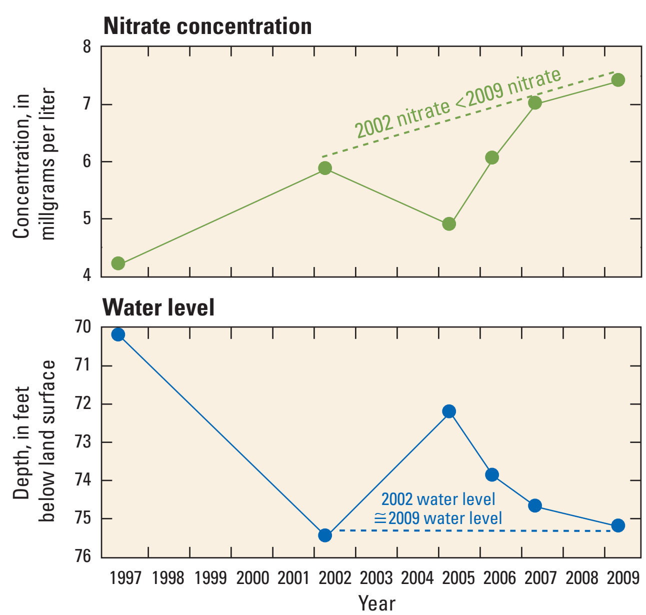


Figure 6–11. Changes in concentrations of nitrate corresponded to changes in water levels in some wells and indicate that some of the variability in concentrations reflects changes in hydrologic conditions. Higher concentrations in 2009 than in 2002 when water levels were similar, however, indicates an increase in nitrate concentrations over time related to nitrogen inputs associated with the overlying urban land use.

Pesticides and VOCs

The occurrence of manmade contaminants at low concentration indicates that shallow groundwater is vulnerable to contamination associated with human activities. Manmade contaminants were detected more commonly and at higher concentrations in the Memphis area, where groundwater is unconfined and groundwater residence times are shorter, than in the other shallow parts of the embayment-uplands and alluvial aquifers.

The occurrence of one or more pesticides or VOCs in 42 percent of samples from shallow wells throughout the embayment-uplands and alluvial aquifers (fig. 6–12) indicates that the shallow groundwater is vulnerable to contamination related to the overlying land-use activities. The number of contaminants detected in shallow groundwater generally increased as the amount of urban and agricultural land near the wells increased, but some wells in areas of predominantly urban and agricultural land use had few if any detections. The variability in the occurrence of manmade contaminants among the shallow aquifers indicates differences in contaminant sources and in aquifer vulnerability to contamination throughout the study area.

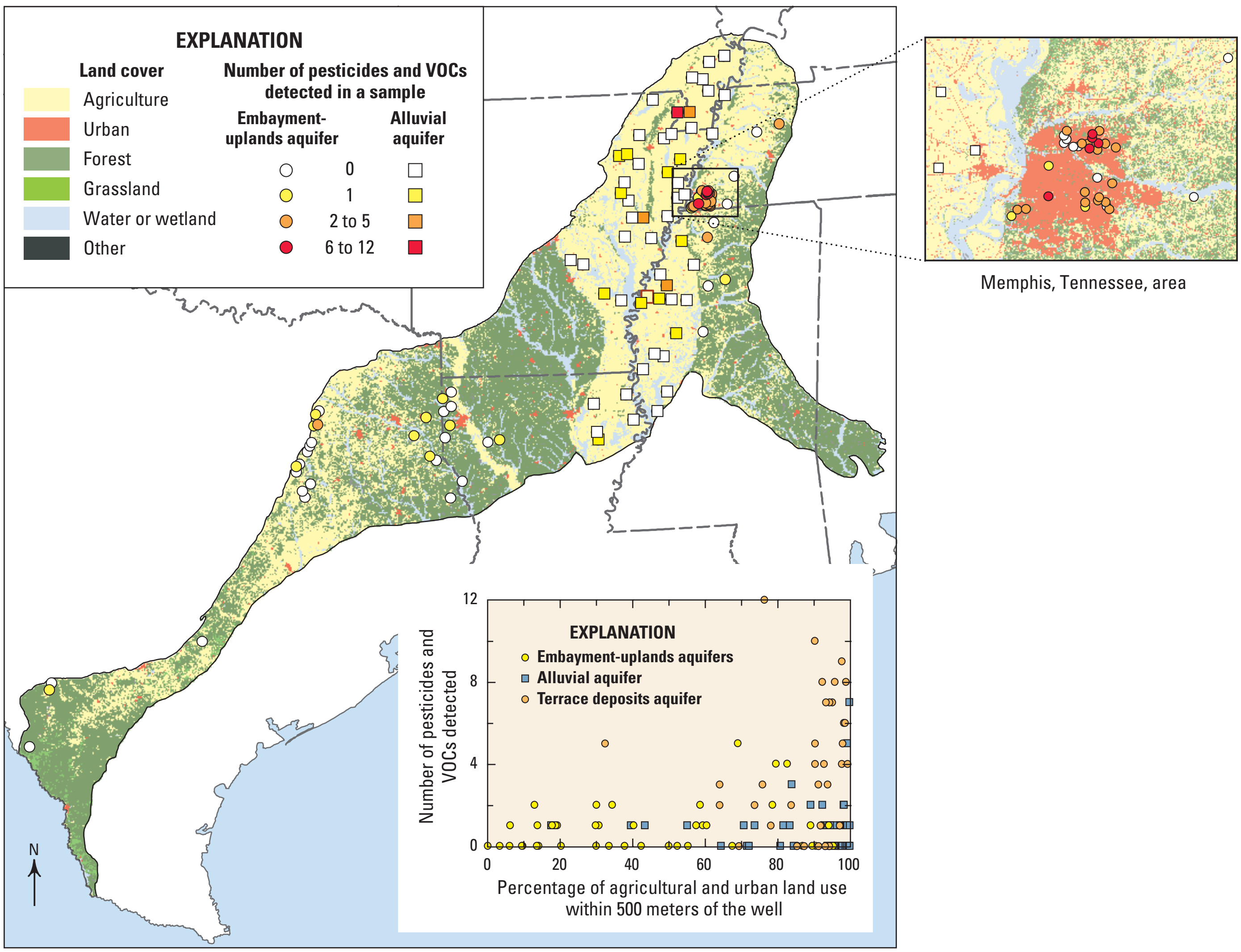


Figure 6–12. In shallow groundwater, pesticides and VOCs were detected most commonly in areas with large amounts of urban and agricultural land use. Differences in hydrogeology between the alluvial aquifer and terrace deposits aquifer account for the more frequent occurrence of these compounds in the Memphis area.

A comparison of the occurrence of pesticides in the alluvial aquifer and shallow groundwater in the Memphis area illustrates the effect of hydrogeology on the vulnerability of shallow groundwater to contamination. Despite widespread pesticide use in the agricultural areas overlying the alluvial aquifer, pesticides were detected in only about 30 percent of samples compared to 75 percent of samples of shallow groundwater in the Memphis area. Fine-grained sediments and organic matter in the upper parts of the Mississippi River Valley alluvium limit the movement of pesticides to the alluvial aquifer by slowing recharge and through sorption of pesticides that move with recharge. Slow recharge rates result in longer groundwater residence times in the alluvial aquifer than in shallow groundwater in the Memphis area.[16, 17, 30] Pesticides were more frequently detected in the Memphis area likely because of the overlying urban land use, which is a source of chemicals, and the relatively young age of the groundwater. In this area, pesticide concentrations were related to the age of the groundwater[29]—the total concentration of pesticides in a sample was higher for those samples containing a higher proportion of recently recharged groundwater (fig. 6–13).

Herbicides commonly detected in shallow groundwater in the Memphis area were similar to those detected in other urban areas across the Nation: atrazine, simazine, deethylatrazine, metolachlor, and prometon.[31] These herbicides were detected more frequently, however, in the Memphis area. For example, simazine was detected in 70 percent of samples from the Memphis area but in only about 20 percent of samples nationally.[31] These herbicides are used for weed control on residential lawns, rights-of-way, and landscape maintenance in commercial and industrial areas.

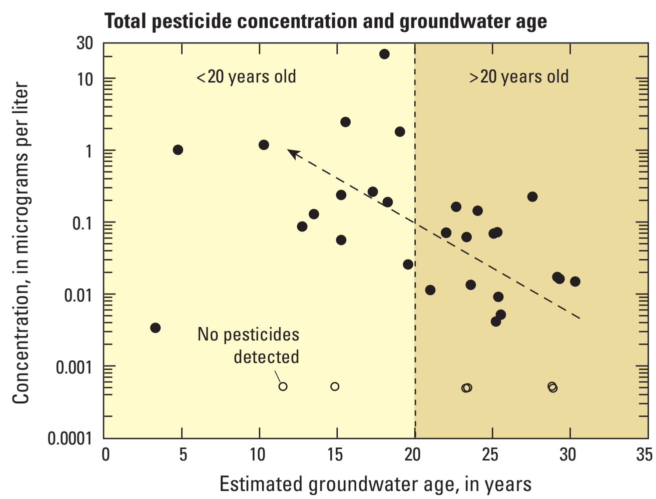


Figure 6–13. In groundwater underlying the Memphis area, the total concentration of pesticides was highest in groundwater less than 20 years old. Concentrations were lower in older groundwater.

Chapter 7: *Understanding Where and Why Key Contaminants Occur in Deep Groundwater Used for Public and Domestic Supply*

Groundwater is the principal source of drinking water for about 8 million people in areas that overlie the embayment-uplands aquifers. These aquifers also are sources of water for industrial use and irrigation. Long-term sustainability of this economically important resource depends in part on understanding if and how groundwater quality changes with increases in use.

This chapter describes the sources of and factors that affect radon, manganese, nitrate, pesticides, and VOCs in deep groundwater in the embayment-uplands aquifers.

The first wells tapping the embayment-uplands aquifers in Memphis, Tennessee, were flowing wells (artesian). Over time, groundwater pumping has lowered water levels by as much as 70 feet and more than 200 feet in a few locations in the study area.

Circa 1890, photographer unknown

Constituents From Geologic Sources

Few constituents derived from geologic sources were detected at concentrations exceeding human-health benchmarks in deep parts of the embayment-uplands aquifers. However, nuisance constituents that can impair taste or stain fixtures were present at concentrations above a recommended level in as many as one-third of the samples.

Radon is one of the few constituents with a geologic source that was measured at concentrations greater than a human-health benchmark in samples from deep parts of the embayment-uplands aquifers. Concentrations of radon were greater than the proposed MCL of 300 pCi/L in 20 of 48 (42 percent) domestic wells; however, no concentrations exceeded the alternative MCL of 4,000 pCi/L. No samples from public-supply wells had a concentration of radon greater than 300 pCi/L. Radon concentrations in domestic wells were higher than those in public-supply wells because of the minerals in the aquifer sediments in which the wells are screened. Domestic wells sampled were located primarily in the western part of the study area in one of the embayment-uplands aquifers with deposits of heavy minerals. These heavy minerals contain uranium and thorium, which are sources of radon. Most of the public-supply wells sampled were in the eastern part of the study area in parts of the embayment-uplands aquifers without heavy mineral deposits.

Manganese was the only constituent other than radon that was measured in water from deep drinking-water wells screened in the embayment-uplands aquifers at a concentration greater than a human-health benchmark. Exposure to high levels of manganese is a human-health concern because of potential effects to neurological function.(14) Concentrations of manganese exceeded the human-health benchmark of 300 μg/L in 2 percent of samples, but concentrations were greater than one-tenth of the benchmark concentration in about 40 percent of samples from drinking-water wells. High concentrations of manganese are related to the anoxic conditions that occur throughout much of the embayment-uplands aquifers. Under anoxic conditions, manganese is released from aquifer sediments into groundwater.

Concentrations of several constituents in samples from deep drinking-water wells exceeded their SMCL. Although elevated concentrations of nuisance constituents are not a concern for human health, they could limit the use of groundwater or increase the cost of water treatment. Concentrations of iron, manganese, and dissolved solids were greater than their SMCLs in more than 20 percent of the samples. Elevated concentrations of these constituents can impart an unpleasant taste or odor to drinking water and can cause staining of clothes and plumbing fixtures. Three other constituents—chloride, fluoride, and aluminum—were detected in 2 percent or fewer of samples at concentrations greater than their respective SMCL.

Anoxic groundwater pumped from the embayment-uplands aquifers for municipal supply is oxygenated as it cascades over aerator trays. The iron and manganese that are dissolved in the water precipitate and are filtered from the water.

Contaminants Related to Human Activities

Much of the groundwater used for drinking-water supply is pumped from wells that are screened at depths greater than 200 ft in the embayment-uplands aquifers. The quality of the groundwater in the deep parts of these confined aquifers generally is good, and relatively few manmade contaminants were detected. This deep groundwater likely was recharged decades to centuries before many of the contaminants measured for this assessment were in use.

Nitrate is one of the most widespread groundwater contaminants across the Nation and is a potential concern in the study area because of the large amount of agricultural land and associated fertilizer use overlying the embayment-uplands aquifers. Anoxic conditions in groundwater throughout most of these aquifers keep nitrate concentrations low; no samples had concentrations greater than the MCL of 10 mg/L as N for nitrate. Groundwater from most wells greater than 200 ft deep had nitrate concentrations near or below 0.06 mg/L as N (detection level). Concentrations of nitrate were greater than 0.5 mg/L as N in samples from a few wells screened between 200 and 400 ft deep, where dissolved-oxygen concentrations were at least 0.5 mg/L (fig. 7–1).

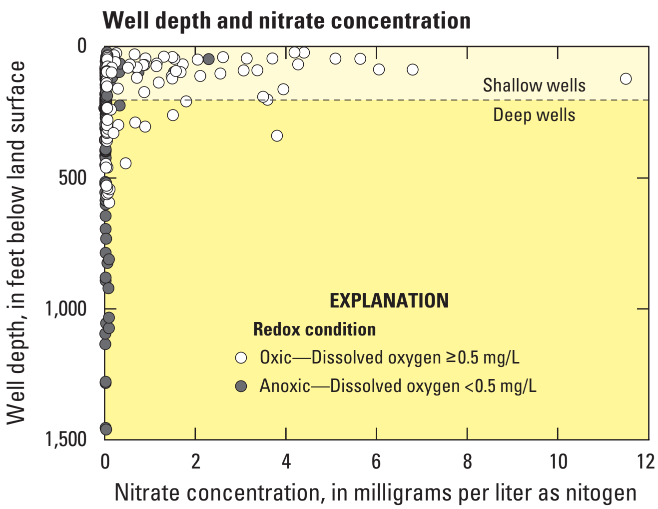


Figure 7–1. The anoxic conditions in deep parts of the embayment-uplands aquifers are favorable for the transformation of nitrate to harmless nitrogen gas. As a result, nitrate was rarely detected in deep groundwater.

Low levels of pesticides and volatile organic compounds in samples from some drinking-water wells indicate that even the deep parts of the aquifers are vulnerable to contamination.

At least one pesticide or VOC was detected in about one-half of the samples collected from deep drinking-water wells screened in the embayment-uplands aquifers. VOCs were detected more commonly than pesticides in samples from both domestic and public-supply wells. The most commonly detected VOC was chloroform, which was detected in about one-fourth of public-supply wells and about one-tenth of domestic wells. This finding is similar to results for samples collected from domestic and public-supply wells across the Nation.[33, 34] Chloroform has industrial uses and is a disinfection by-product formed during water treatment. Its widespread occurrence in groundwater may be related to the recharge of chlorinated water to aquifers.[12] Atrazine and simazine, the most commonly detected pesticides, were detected in 7 and 5 percent, respectively, of samples of deep groundwater. These herbicides generally were detected in public-supply and domestic wells at concentrations less than 0.1 µg/L, which is more than 10 times lower than their MCLs. The insecticide dieldrin was the only pesticide or VOC detected at a concentration greater than its human-health benchmark of 0.002 µg/L; one public-supply well had a concentration of dieldrin of 0.003 µg/L.

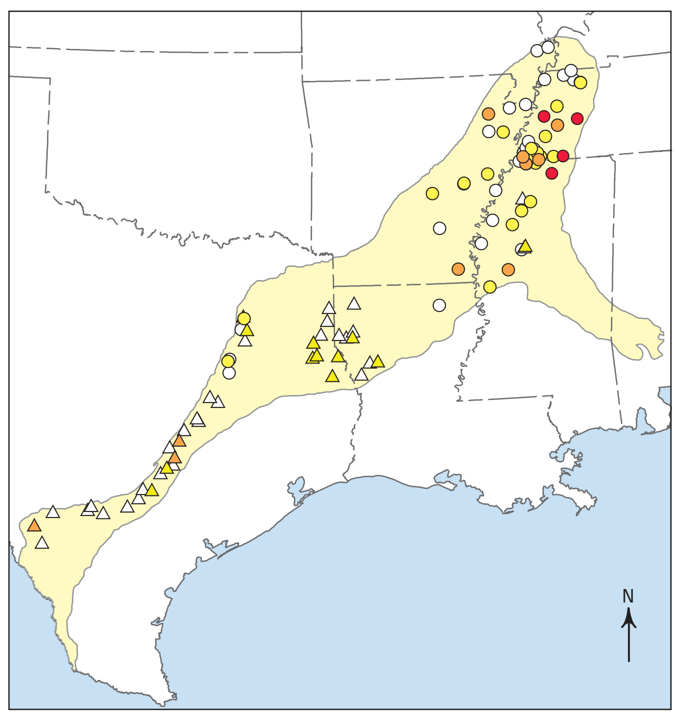
Samples from public-supply wells contained more pesticides and VOCs than did samples from domestic wells. Two or more compounds were detected in about 18 percent of samples from public-supply wells, and as many as 10 compounds were detected in some samples. Only about 5 percent of the domestic wells had two or more compounds detected (fig. 7–2). The larger number of compounds and greater frequency of detection in the public-supply wells likely are because these wells pump much larger volumes of water than do domestic wells and, as a result, have larger contributing areas with multiple sources of organic contaminants.[12] More agricultural land use and higher recharge rates in the eastern part of the study area than in the western part also could account for some of the differences in occurrence of these manmade contaminants. Public-supply wells with the largest number of compounds detected were located near areas where aquifers of the embayment-uplands aquifers are exposed at land surface, such as the eastern part of the aquifer in Tennessee and Mississippi.

Figure 7–2. Pesticides and VOCs were detected more commonly in public-supply wells than in domestic wells, probably because public-supply wells have a higher pumping capacity and, therefore, a larger contributing area with more potential sources of contaminants.

EXPLANATION

Embayment-uplands aquifers

Domestic wells	Public-supply wells	Compounds detected
△	○	No pesticides or VOCs
▲ (yellow)	● (yellow)	1
▲ (orange)	● (orange)	2 to 3
	● (red)	More than 3



Water quality affects drinking-water availability

"Water, water every where, nor any drop to drink." This verse from the "Rime of the Ancient Mariner" was written about the ocean, but it applies as well to water resources in many parts of the Nation. Even when water is plentiful, it's not truly available for use unless the quality is acceptable for that use. Both water quality and availability are essential to maintaining water supply for municipal, domestic, agricultural, aquatic life, and recreational use. Where water quality is poor, there are options to reduce or remove harmful constituents, but they come with costs. Treatment costs and options for addressing groundwater contamination vary depending on the type of contaminant and specifics of water-supply management, but can cost thousands of dollars per household.

Some options that domestic well owners and public-supply providers can take include

- Installing and maintaining household treatment devices
- Buying drinking water, either in bottles or from another supplier
- Blending water—diluting a contaminated source with water from an uncontaminated source
- Locating and developing a new, uncontaminated source of drinking water
- Building or upgrading and operating a treatment plant to remove contaminants

The cost of groundwater contamination for a public-supply provider

In the summer of 1986, trichloroethene (TCE), a solvent used to clean and degrease metal parts at a nearby manufacturing facility, was detected in samples from two supply wells at one of the water-treatment plants for the Town of Collierville, Tennessee. Air strippers were installed by the responsible party to treat the groundwater to meet Safe Drinking Water Act standards for continued use for public supply. These supply wells are located at the edge of a plume of TCE contamination in groundwater and, because of the amounts of groundwater pumped, withdrawals by the two wells keep the plume from migrating further from the site.

In 2002, chromium, associated with a facility that manufactured battery casings, was detected in samples from these same two supply wells. Concentrations of chromium were less than but approaching the Maximum Contaminant Level and high enough that the water treated for TCE contamination could no longer be used for drinking and instead began to be discharged to the sanitary sewer system. To make up for the 1.5 million gallons a day of lost production from the wells and to meet peak demands for the part of the area served by these wells, a tank to store additional treated water from the other four treatment plants was built and high capacity pumps were installed at a cost of about $1.4 million. The two contaminated wells continue to be used to capture and contain the TCE plume and the Town of Collierville agreed to be responsible for continued operation and maintenance of the wells.

Photograph courtesy of Town of Collierville

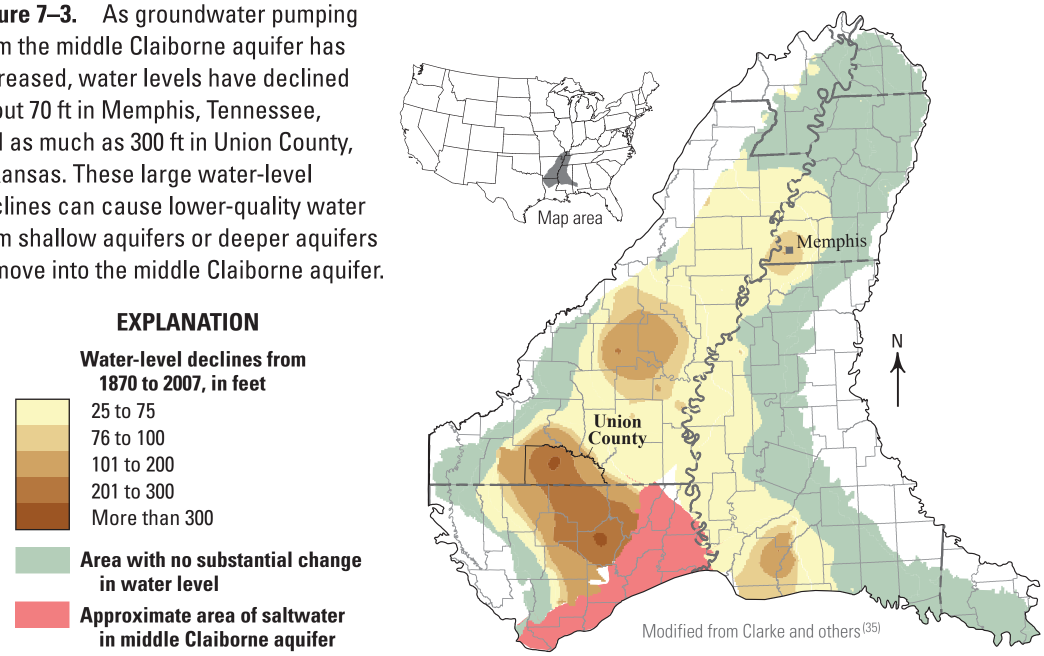
An additional water storage tank (the larger tank pictured) had to be built at this Collierville water plant when two wells were taken out of service because of chromium contamination. Air strippers to remove TCE from well water are located behind the smaller storage tank.

Aquifers in Areas of Prolonged High-Volume Pumping May Be Vulnerable to Contamination

Groundwater withdrawals from the embayment-uplands aquifers have lowered water levels by as much as 300 ft in some areas. Groundwater quality in these areas can be affected by increased recharge and downward movement of contaminants in shallow groundwater or from changes in groundwater-flow directions.

Groundwater withdrawals from the embayment-uplands aquifers for municipal supply and industrial uses have increased over time and in 2000 totaled about 944 Mgal/d.(7) As a result of these large withdrawals of groundwater, water levels in some parts of the study area have declined by as much 300 ft (fig. 7–3). Large water-level declines in deep aquifers increase the potential for contaminants in shallow groundwater to move downward. Alternatively, water from underlying aquifers can move upward to an overlying pumped aquifer. Fresh groundwater in much of the southern part of the embayment-uplands aquifers overlies saline or saltwater, and upward movement of saltwater could make the aquifers unsuitable for continued use as a drinking-water source.

Figure 7–3. As groundwater pumping from the middle Claiborne aquifer has increased, water levels have declined about 70 ft in Memphis, Tennessee, and as much as 300 ft in Union County, Arkansas. These large water-level declines can cause lower-quality water from shallow aquifers or deeper aquifers to move into the middle Claiborne aquifer.



Pumping increases the movement of shallow groundwater into the deeper aquifer used for drinking water in the Memphis area

Deep groundwater in the embayment-uplands aquifers is the primary source of water for about 1 million people in the Memphis area. Withdrawals have increased steadily from initial use of the aquifers for water supply in 1886 until the mid-1970s when the overall rate of withdrawal in the area stabilized.(35) Pumping for public supply has continued to increase since 1970, but these increases have been offset by lower pumping rates for industrial use. In 2005, about 185 Mgal/d were pumped from the embayment-uplands aquifers for public supply in the Memphis area, nearly all of which came from the middle Claiborne aquifer. This pumping lowered water levels by as much as 70 ft,(36) causing groundwater to move downward from the overlying shallow aquifer.(9)

A confining layer composed primarily of clay limits the downward movement of groundwater and contaminants throughout much of the Memphis area. Where the confining layer is thin or absent, shallow groundwater can move downward into the middle Claiborne aquifer.(9, 27, 37) Pesticides and VOCs have been detected in the middle Claiborne aquifer in only a few locations in the Memphis area,(9, 38, 39, 40) but these contaminants were detected relatively frequently in samples of shallow groundwater (chapter 6).

Changes in specific conductance of groundwater over time indicate areas where the middle Claiborne aquifer is vulnerable to leakage from the overlying shallow aquifer (fig. 7–4). Specific conductance is a general measure of dissolved solids in water and can be used to trace movement of the shallow groundwater, which has greater specific conductance than the middle Claiborne aquifer. An increase in specific conductance over time is an indication that the aquifer in that area is especially vulnerable to contamination from chemicals that can move with shallow groundwater to deeper parts of the aquifer used for public supply. Specific conductance increased between 2000 and 2010 in some parts of the Memphis area. Prior to these changes, groundwater in these areas was not thought to be vulnerable to contamination from the shallow aquifer because specific conductance had been stable. These changes illustrate the value of long-term hydrologic and water-quality monitoring and data collection.

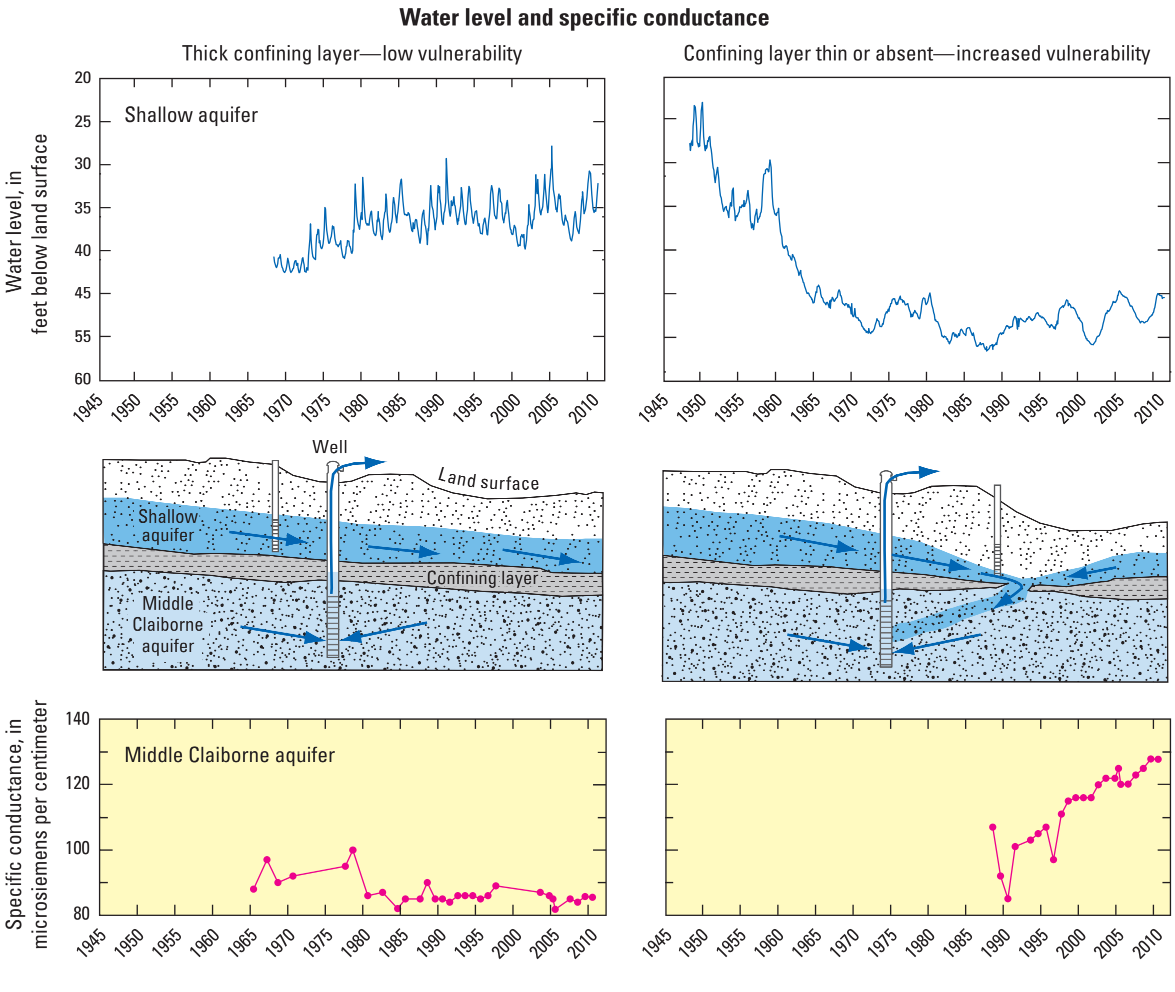


Figure 7–4. Long-term water level and specific conductance data indicate areas that are vulnerable to contamination from shallow groundwater. Where the confining layer is thick, changes in water levels in the overlying shallow aquifer are not affected by withdrawals from the underlying middle Claiborne aquifer in the Memphis, Tennessee area, and specific conductance in samples from the middle Claiborne aquifer is relatively stable. Where the confining layer is thin or absent, water levels in the shallow aquifer have declined in response to lower water levels in the middle Claiborne aquifer. As groundwater with a higher specific conductance from the shallow aquifer has moved downward, specific conductance has increased over time in samples from the middle Claiborne aquifer.

Withdrawals from the middle Claiborne aquifer in Arkansas and Louisiana have caused saltwater to move into the aquifer

In southern Arkansas and northeastern Louisiana, water levels have declined in some areas more than 300 ft (fig. 7–5) as a result of pumping for municipal and industrial uses.[41] Because the embayment-uplands aquifers are the principal source of water supply for about 270,000 people in this region,[42, 43] large water-level declines in response to long-term pumping have raised concerns about the long-term availability and quality of water from these aquifers.

Chloride concentrations in the middle Claiborne aquifer have increased in parts of Union County, Arkansas,[44] and in northeastern Louisiana (fig. 7–5). Changes in chloride concentrations observed in these areas are not related to the downward movement of shallow groundwater because the overlying confining layer limits downward movement of shallow groundwater in this area. Instead, the large declines in water levels have caused saltwater to move either laterally from more saline parts of the aquifer or upward from underlying aquifers with higher concentrations of chloride.[41] Chloride concentrations in the embayment-uplands aquifers generally increase with depth and proximity to the coast. Groundwater pumping in Winn Parish, Louisiana, has lowered water levels to the point that the saltwater-freshwater interface has moved as indicated by increasing concentrations of chloride. Concentrations of chloride have increased in groundwater in the areas between the largest water-level declines and the saltwater-freshwater interface, indicating lateral movement of saltwater (see sidebar, Saltwater intrusion, p. 55). In contrast, increases in concentrations of chloride in Ouachita Parish have occurred primarily in the area of largest water-level declines, which indicates that vertical movement or upwelling of saltwater (see sidebar, Saltwater intrusion) is responsible for the increase in chloride concentrations.

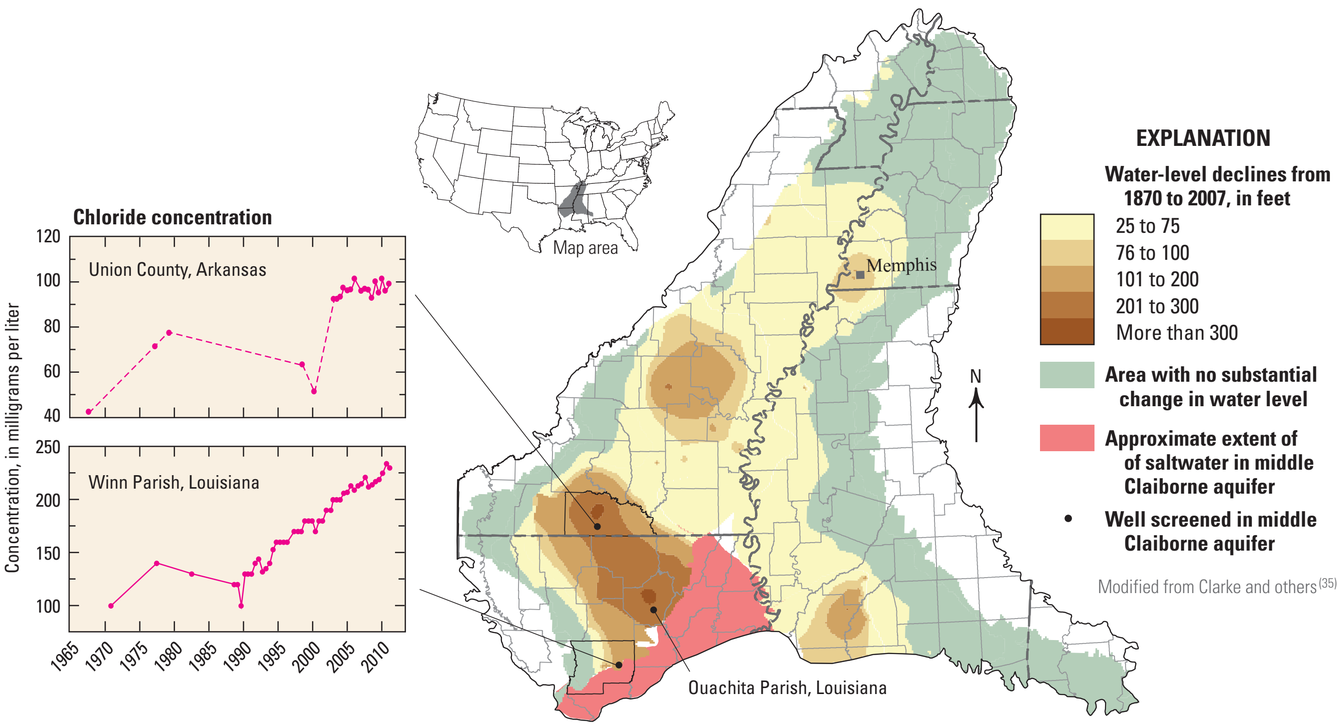
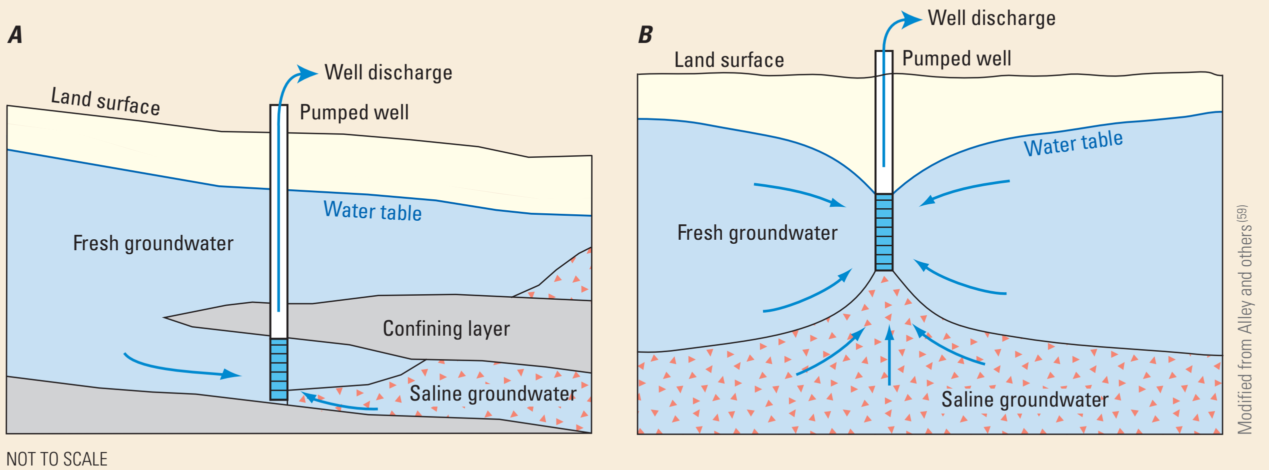


Figure 7–5. Large amounts of groundwater pumping have lowered water levels and caused saltwater to move into areas of freshwater in the middle Claiborne aquifer from other parts of the middle Claiborne aquifer or underlying aquifers in Louisiana and Arkansas. Water-resource managers and water users have implemented water-conservation measures and have begun using surface water for industrial use to mitigate the water-level declines and changes in water quality.

Because of these large water-level declines and changes in water quality, industries, municipal water suppliers, and local and State agencies in Arkansas and Louisiana are working to ensure the sustainability of this groundwater resource. In Arkansas, water-conservation practices and new infrastructure to supplement nonpublic-supply groundwater use with surface water were initiated in 2004 to address water-level declines in the aquifer.(45) About $65 million was spent to treat and pipe surface water 15 miles from the Ouachita River to three industries that were using groundwater. The associated reductions in groundwater use have resulted in water levels recovering as much as 45 ft in the area since about 2004. In Louisiana, the Sparta Ground Water Commission, which includes representatives from several parishes in northern Louisiana, was established in 1999. Its mission is to conserve, protect, restore, and maintain the Sparta (middle Claiborne) aquifer as a high-quality source of drinking water in northern Louisiana. As a result of conservation and water reuse efforts by local industries since about 2000, groundwater levels have recovered in several locations.

Saltwater intrusion

Saltwater intrusion is the movement of saline water into freshwater aquifers and commonly is caused by groundwater pumping. Throughout most of the study area, the source of saltwater is not seawater, but rather deep groundwater with high dissolved solids and elevated chloride content that underlies the freshwater. Freshwater is less dense than saltwater and floats above it. At the lower limit of freshwater, a wedge is formed, commonly called the freshwater-saltwater interface. Under natural conditions, recharge and the flow of fresh groundwater are adequate to keep saltwater encroachment from occurring. Large withdrawals, however, can create cones of depression in water levels around pumping centers, which may create conditions favorable for saltwater movement into freshwater parts of an aquifer and cause pronounced changes in the water quality.



Large water-level declines from groundwater pumping can cause saline water to move *A*, laterally or *B*, upward into the well resulting in increased concentrations of chloride and dissolved solids in the pumped well.

For more information about NAWQA Principal Aquifer studies

Groundwater quality for many of the Nation's Principal Aquifers is characterized in U.S. Geological Survey Circular 1360. This report and links to other Principal Aquifer circulars are available at *http://water.usgs.gov/nawqa/pasumm/*.

More than 2,000 NAWQA Program reports are available online at *http://water.usgs.gov/nawqa/bib/*.

Photograph by Alan M. Cressler, USGS

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Photograph by Alan M. Cressler, USGS

Glossary

A

anoxic Water with no dissolved oxygen or a very low concentration (less than 0.5 milligram per liter) of dissolved oxygen.

apparent groundwater age The time elapsed since the recharge water became isolated from the atmosphere. The term “age” is normally qualified with the word “apparent” to signify that the accuracy of the determined age depends on many variables.

aquifer A geologic formation, group of formations, or part of a formation that contains a sufficient amount of saturated permeable material (for example, soil, sand, gravel and (or) rock) to yield substantial quantities of water to wells and springs.

B

base flow Groundwater seepage into a stream or river. The continual contribution of groundwater to streams or rivers is an important source of streamflow between rain events.

C

common assessment level A single concentration threshold used to establish an equal basis for comparing detection frequencies among multiple chemicals. Use of a common assessment level avoids biases in detection frequencies caused by one compound having a lower detection level than another. Also sometimes referred to as a “common detection level.”

confining layer Geologic material with little or no permeability or hydraulic conductivity. Water does not pass through this layer or the rate of movement is extremely slow.

D

degradate A compound formed by the transformation of a parent compound, typically an organic contaminant or another degradate, by chemical, photochemical, or biological reactions.

denitrification The bacterial reduction of dissolved nitrate to nitrogen gas. Denitrification is the primary process by which nitrate can be eliminated naturally in groundwater.

discharge The rate of flow of surface water or groundwater past a given point at a given moment, expressed as volume per unit of time. Also, the outflow from an aquifer, spring, or well or up through a streambed.

E

evapotranspiration Loss of water from soil by evaporation and plant transpiration combined.

F

flow path The route or pathway of water flowing through the hydrologic system. Typically refers to subsurface (groundwater) flow.

G

groundwater Water that exists beneath the land surface, but most commonly refers to water in fully saturated soils and geologic formations.

groundwater age *See* apparent groundwater age.

groundwater residence time The average amount of time it takes for groundwater to move from the point where it enters the aquifer to a specific point of discharge, such as a well or stream.

H

half-life The time required for the concentration of a compound in a given environmental medium to be reduced to one-half of its original value by one or more processes, such as degradation or transport into another environmental medium.

Health-Based Screening Level (HBSL) An estimate of concentration (for a noncarcinogen) or concentration range (for a carcinogen) in water that (1) may be of potential human-health concern, (2) can be used as a threshold value against which measured concentrations of contaminants in ambient groundwater samples can be compared, and (3) is consistent with U.S. Environmental Protection Agency Office of Water methodologies.

human-health benchmark A threshold concentration above which the concentration of a contaminant in drinking water could have adverse effects on human health. Treatment or other measures can be used before the water is consumed to lower the concentration of the contaminant below the benchmark.

hydrogeologic unit A body of rock distinguished and characterized by its porosity and permeability. Also called a hydrostratigraphic unit.

hydrogeology The geologic and hydrologic features that control the movement of water, solutes, and small particles through the subsurface.

hydrologic system The assemblage of pathways by which water travels as it circulates beneath, at, and above the Earth's surface during precipitation, runoff, evaporation, infiltration, transpiration, and groundwater discharge.

I

infiltration Movement of water, typically downward, into soil or porous rock.

irrigation return flow The part of irrigation water applied to the surface that is not taken up by plants or lost by evaporation and that migrates to an aquifer or surface-water body.

L

land-use study A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program to assess the effects of a specific land-use type (generally agricultural or urban) on groundwater quality, in most cases by sampling groundwater from monitoring wells that tap water from or near the water table.

M

major aquifer A regionally extensive subsurface geologic formation or group of formations that is used, or has the potential to be used, as a substantial groundwater resource.

major aquifer study A study by the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program that involves sampling of water at 20 to 30 domestic and (or) public-supply wells that withdraw water from major aquifers. The major aquifer studies represent a mix of land uses and target water that is used for drinking-water supply.

Maximum Contaminant Level (MCL) Maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are enforceable standards established by the U.S. Environmental Protection Agency.

milligrams per liter (mg/L) A unit expressing the concentration of a chemical constituent as weight (milligrams) of constituent per unit volume (liter) of water; equivalent to one part per million in most streamwater and groundwater. One thousand micrograms per liter (µg/L) is equivalent to 1 mg/L.

monitoring well A well used to measure water quality or groundwater levels continuously or periodically. Not typically used as a source of drinking water. Sometimes referred to as an "observation well."

N

nonpoint source A contaminant source that is not a discrete point, such as a pipe, ditch, or tunnel. Areas of fertilizer and pesticide applications, atmospheric deposition, and stormwater runoff are examples of sources of nonpoint contamination.

nutrient An element or compound essential for animal and plant growth. Common nutrients include nitrogen, phosphorus, and potassium, such as are found in fertilizer.

O

oxic Water with a concentration of dissolved oxygen greater than or equal to 0.5 milligram per liter.

P

pesticide Any substance, organic or inorganic, used to kill plant or animal pests.

point source A stationary location or fixed facility from which contaminants are discharged, for example, a pipe, ditch, ship, ore pit, or factory smokestack.

predevelopment The time prior to substantial groundwater development by humans or effects of agricultural, urban, suburban, or other human-related land uses.

Principal Aquifer A regionally extensive aquifer or aquifer system that has the potential to be used as a source of potable water. A Principal Aquifer can be composed of one or more major aquifers.

public-supply well A privately or publicly owned well that provides water for public use to (1) a community water system, (2) a transient noncommunity water system, such as a campground, or (3) a nontransient, noncommunity system, such as a school.

R

radioactive decay The spontaneous emission of particles (alpha or beta) and gamma rays from an atom with an unstable nucleus (radionuclide).

recently recharged groundwater Groundwater that was recharged after 1952, as indicated by tritium concentrations greater than 0.5 tritium unit.

recharge The addition of water to the saturated zone naturally by precipitation or runoff or artificially by spreading or injection. Also, the water that is added.

reduction-oxidation (redox) Chemical reactions that involve the transfer of electrons from one chemical species to another, resulting in a change in the valence state of the species. Redox processes in groundwater often are microbially facilitated.

S

saturated zone The region in the subsurface in which all the spaces (pores and fractures) are filled with water and are under pressure greater than atmospheric pressure.

Secondary Maximum Contaminant Level (SMCL) Guidelines set by the U.S. Environmental Protection Agency for concentrations of "nuisance" constituents in drinking water that may cause unwanted effects, such as unpleasant taste, color, or odor; discoloration of skin or teeth; or corrosion or staining of plumbing fixtures. Public drinking-water systems are recommended but not required to comply with these guidelines.

subsurface The region of earth materials beneath the land surface that encompasses the soil and unsaturated and saturated zones.

sustainability The amount of groundwater that will be available to support future uses of a particular aquifer or groundwater resource. The development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

T

tritium unit (TU) A measure of the concentration of tritium (^3H) equal to one ^3H atom in 1,018 atoms of hydrogen (H), or 3.24 picocuries per liter.

U

unsaturated zone A subsurface zone containing both water and air. The unsaturated zone is limited above by the land surface and below by the water table.

V

volatile organic compound (VOC) An organic chemical that has a high vapor pressure relative to its water solubility. VOCs include components of gasoline, fuel oils, lubricants, organic solvents, fumigants, some inert ingredients in pesticides, and some by-products of chlorine disinfection.

vulnerability The tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer. The vulnerability of a groundwater resource to contamination depends both on the intrinsic susceptibility of the resource and on the locations and types of human and geologic sources of contaminants, locations of wells, and characteristics of the contaminant(s).

W

watershed The land area that drains into a particular stream, river, lake, estuary, or coastal zone.

water table The upper surface of the saturated zone below which all voids (spaces) are filled with water.

Appendix 1. Study Components of the Mississippi Embayment–Texas Coastal Uplands Aquifer System and Mississippi River Valley Alluvial Aquifer Water-Quality Assessment

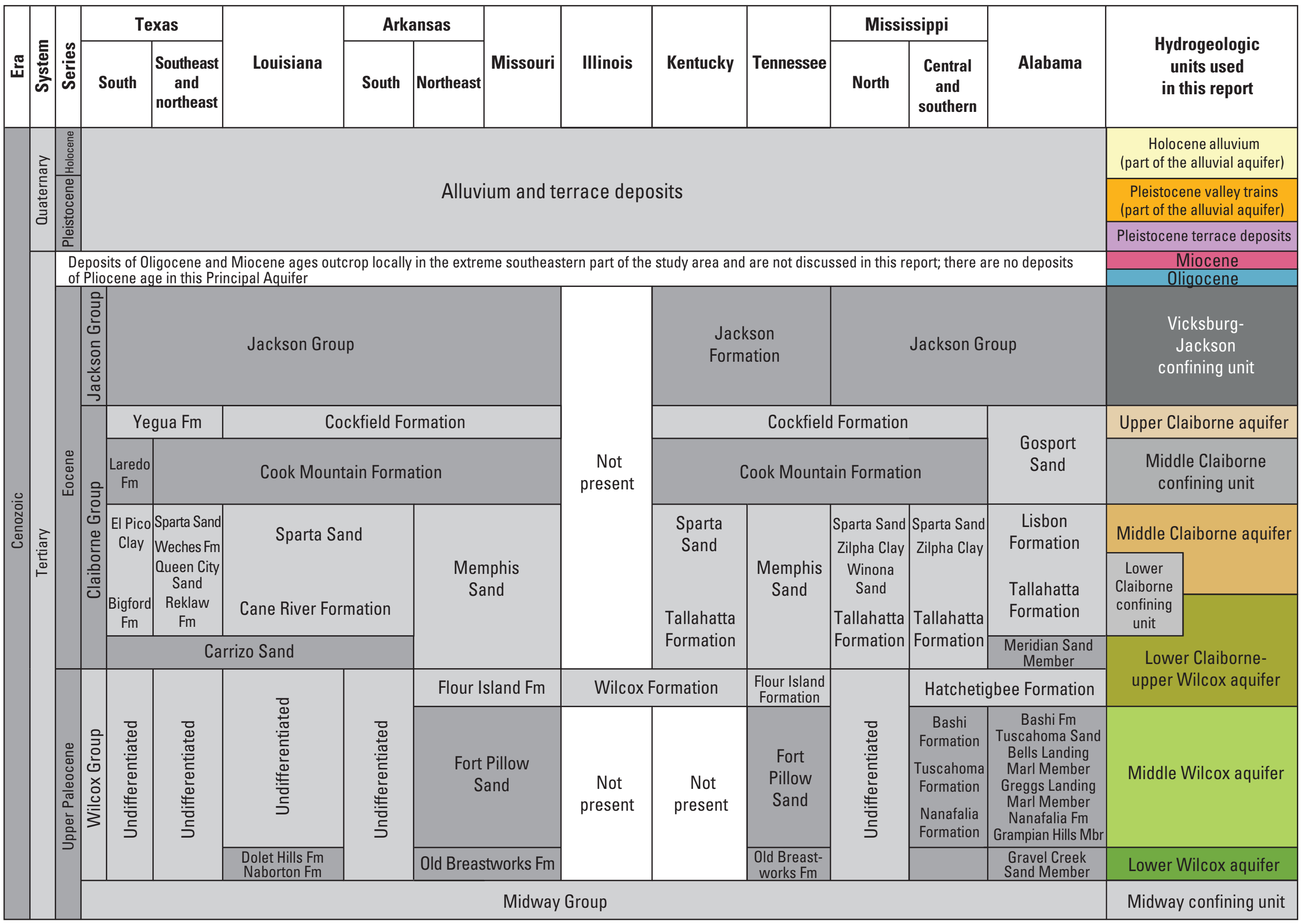
[F, field parameters including water temperature, specific conductance, pH, alkalinity, turbidity, and dissolved oxygen; M, major ions; N, nutrients; D, dissolved organic carbon; TE, trace elements; P, pesticide compounds; V, volatile organic compounds; R, radon; SI, stable isotopes of oxygen and hydrogen; MB, microbiological; RA, radium; A, age tracers other than tritium; T, tritium; AC, other organic compounds]

Study component	Study location	Study purpose	Water-quality parameters measured	Year sampled	Number of wells sampled	Well types
Major aquifer study	Eastern Texas and western Louisiana	Broadly characterize water quality in the Mississippi embayment–Texas coastal uplands aquifer system	F, M, N, D, TE, P, V, R,* SI,* MB,† RA†	2004	30	Domestic
Major aquifer study	Eastern Texas	Broadly characterize water quality in the Mississippi embayment–Texas coastal uplands aquifer system	F, M, N, D, TE, P, V, SI,* A†	1994	23	Mostly domestic and public supply
Major aquifer study	Southwest Texas	Broadly characterize water quality in the Mississippi embayment–Texas coastal uplands aquifer system	F, M, N, D, TE, P, V, R,* T,* SI,* A,† MB,† RA†	2008	30	Domestic
Major aquifer study	Eastern Arkansas and western Mississippi	Broadly characterize water quality in the Mississippi River Valley alluvial aquifer—Pleistocene valley trains subunit	F, M, N, D, TE, P, V, R, T, SI	1998	29	Irrigation, public supply, and domestic
Major aquifer study	Eastern Arkansas and western Mississippi	Broadly characterize water quality in the Mississippi River Valley alluvial aquifer—Holocene alluvium subunit	F, M, N, D, TE, P, V, R,* T,* SI*	1998	25	Irrigation, public supply, and domestic
Major aquifer study	Eastern Arkansas, western Tennessee and Mississippi, southern Missouri	Broadly characterize water quality in the Mississippi embayment–Texas coastal uplands aquifer system	F, M, N, D, TE, P, V, R,* T,* SI*	1996	29	Public supply
Major aquifer study	Western Tennessee and western Mississippi	Broadly characterize water quality in the Mississippi embayment–Texas coastal uplands aquifer system	F, M, N, D, TE, P, V, T,* SI,* A,† MB,† RA†	2007	28	Mostly domestic and public supply
Land-use study	Memphis, Tennessee	Characterize the quality of recently recharged water in an urban setting	F, M, N, D, TE, P, V, R, T, SI	1997, 2006	33	Monitoring
Source water-quality assessment	Memphis, Tennessee	Characterize the quality of water used for public supply in the Mississippi embayment–Texas coastal uplands aquifer system	F, D, P, V, AC	2005	15	Public supply

*Analyzed in samples collected during 1991–2001 only.

†Analyzed in samples collected during 2002–09 only.

Appendix 2. Stratigraphic Column and Local Aquifer Names for the Mississippi Embayment–Texas Coastal Uplands Aquifer System



Modified from Hosman and Weiss,[46] Ryder,[47] Warwick and others,[48] and Renken.[5]

Appendix 3. Water-Quality Properties and Constituents Measured, a Summary of Data, and Complete Data Archive for 1994–2008

Water-quality properties and constituents measured and a summary of data for 1994–2008, including laboratory reporting levels and human-health benchmarks for drinking water, are presented only online. A data summary is available for download at *http://pubs.usgs.gov/circ/1356/*. The complete data archive is available at *http://pubs.usgs.gov/circ/1360/*.[61]

Appendix 4. Water Quality of the Mississippi Embayment–Texas Coastal Uplands Aquifer System and Mississippi River Valley Alluvial Aquifer in a National Context

Principal Aquifer (number of samples)

(NA) Wells of this type were not sampled for this constituent

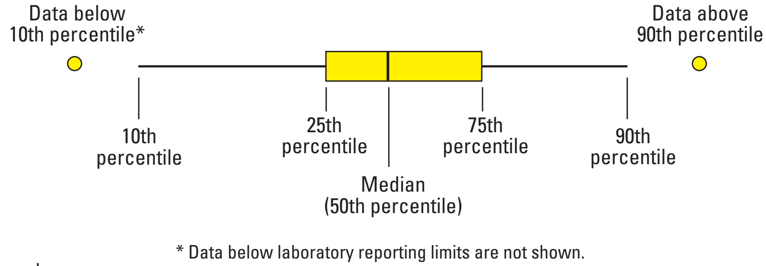
U.S. Environmental Protection Agency contaminant levels for drinking water

- - - - - MCL Maximum Contaminant Level

- - - - - SMCL Secondary Maximum Contaminant Level

- - - - - PMCL Proposed Maximum Contaminant Level

- - - - - AMCL Proposed Alternative Maximum Contaminant Level



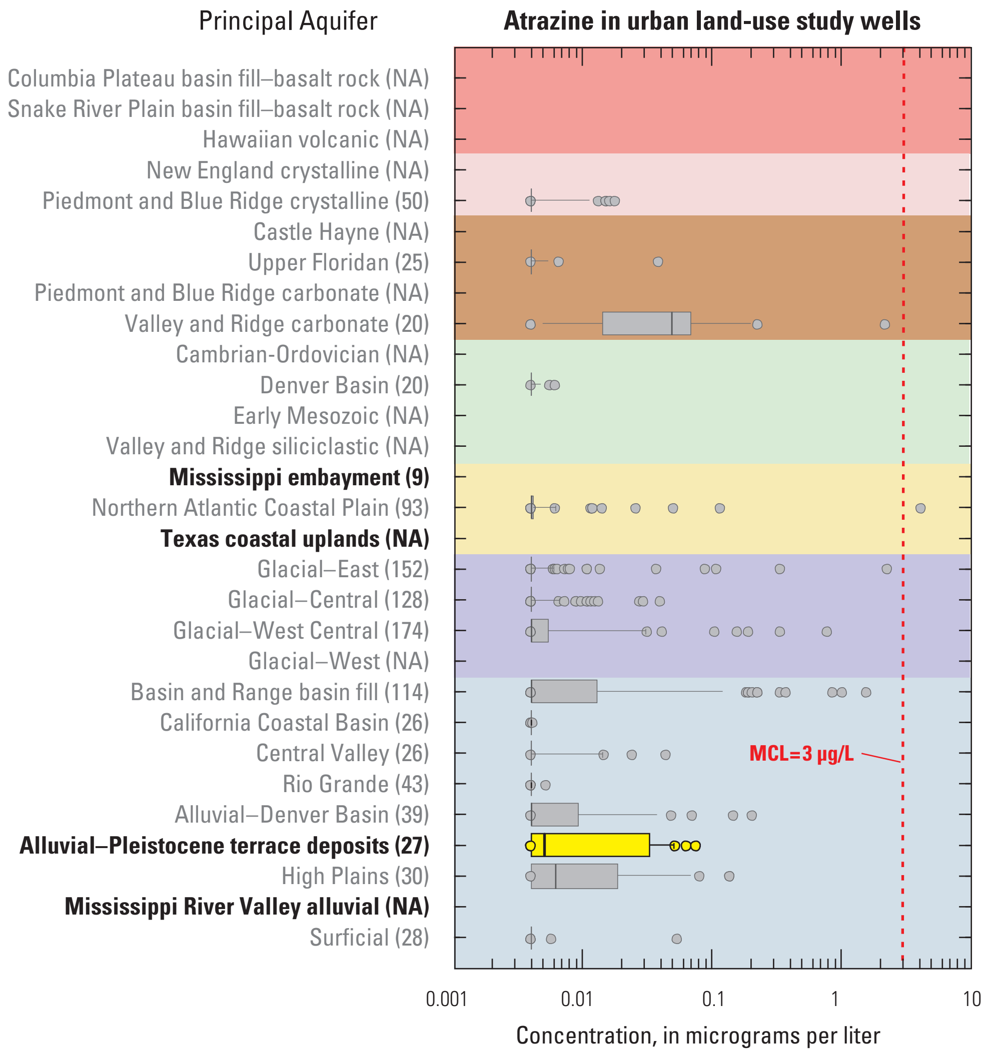
Lithology

Basalt and volcanics** | Crystalline | Carbonate | Sandstone | Semiconsolidated sand and gravel | Glacial unconsolidated sand and gravel | Unconsolidated sand and gravel (nonglacial)

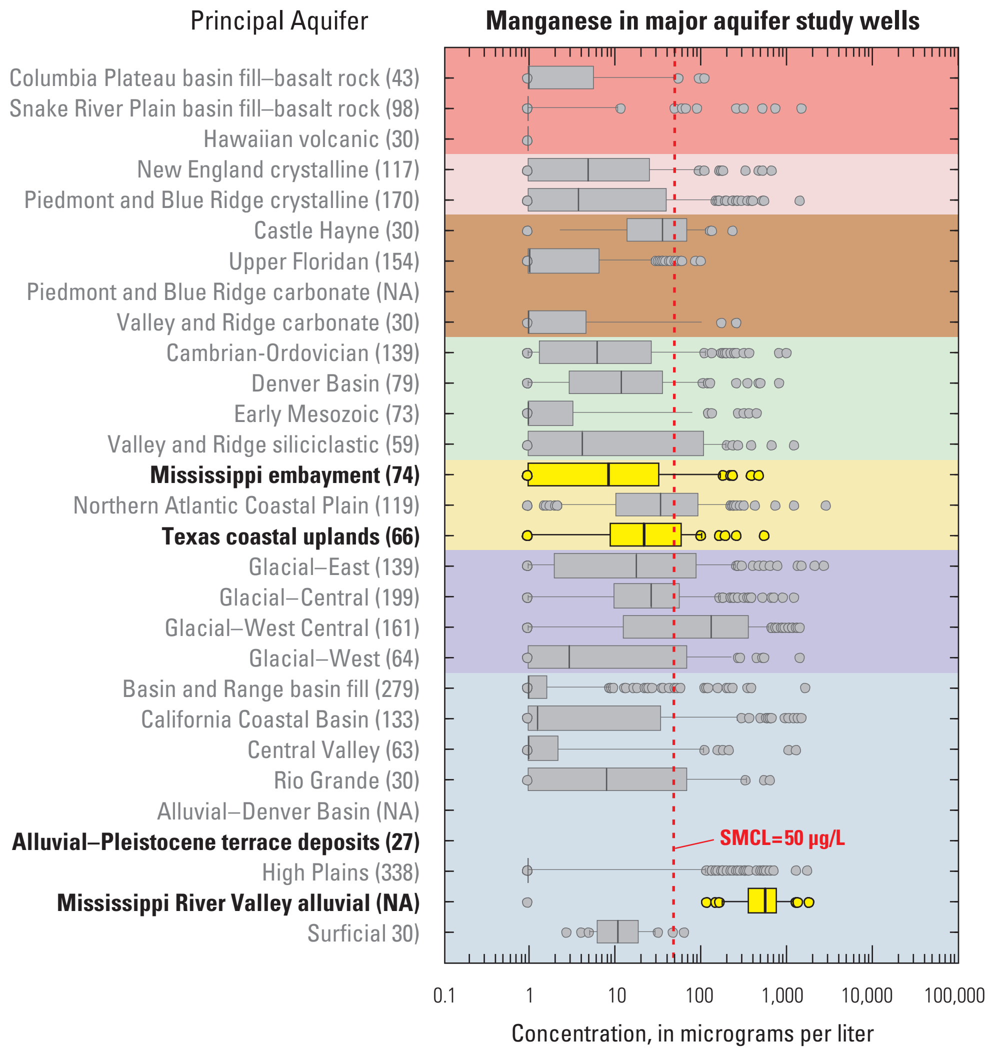
This appendix shows graphical comparisons of chemical concentrations (1991 to 2010) for selected inorganic and organic constituents of potential health or aquatic-life concern in selected Principal Aquifers of the United States. For each constituent, the concentration data are grouped according to five well types: agricultural land-use study wells (includes shallow agricultural monitoring wells), urban land-use study wells (includes shallow urban monitoring wells), major aquifer study wells, domestic wells, and public-supply wells. For each well type, the aquifers also are grouped according to aquifer lithology: basalt and volcanics,** crystalline, carbonate, sandstone, semiconsolidated sand and gravel, glacial unconsolidated sand and gravel, and unconsolidated sand and gravel (nonglacial). Data for a particular compound were not plotted if there were fewer than 10 samples for a particular well network in a Principal Aquifer; not all Principal Aquifers for which data were available are shown. Note that analytical detection limits varied among the constituents and that the number of samples for a constituent can vary greatly between Principal Aquifers. The data used in this appendix and boxplots for additional constituents are available at *http://pubs.usgs.gov/circ/1360/*.

** Note: Two of the Principal Aquifers in this group include limited samples from basin-fill aquifers within the extent of the basaltic aquifer.

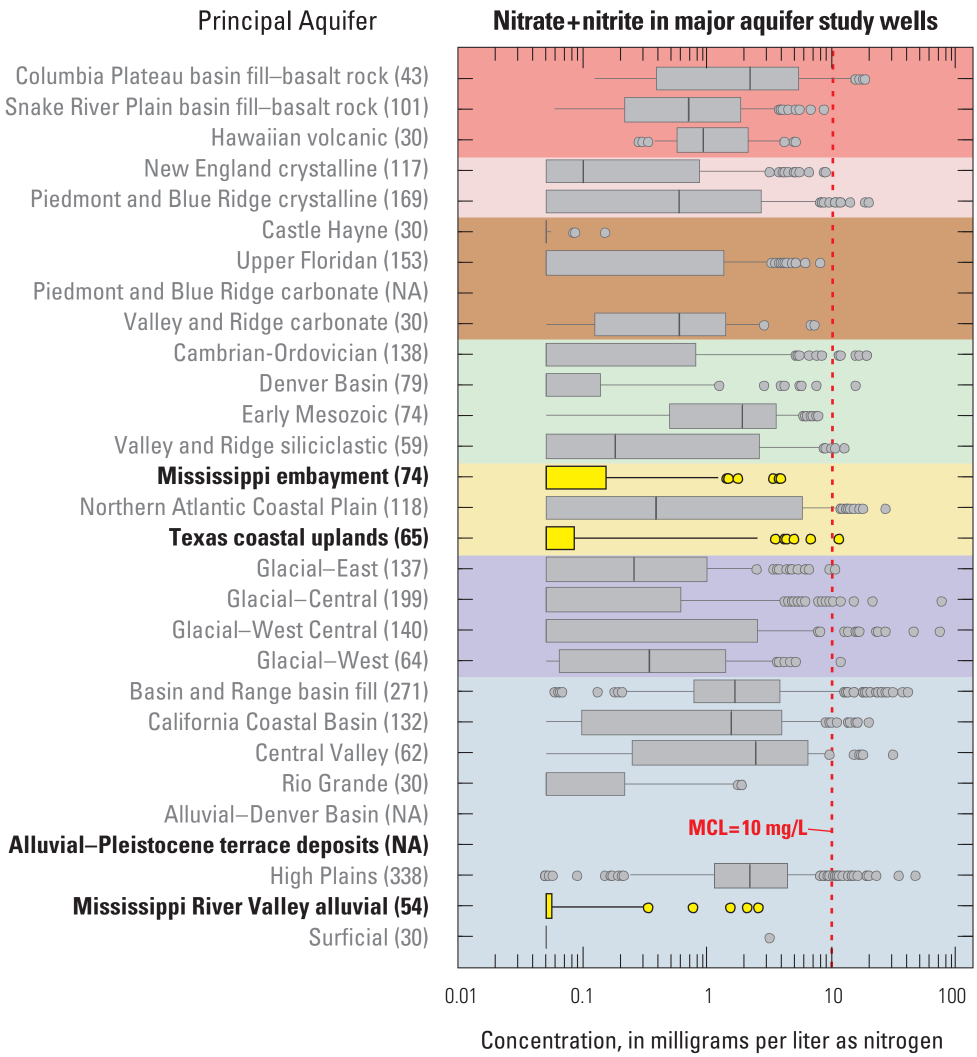
Atrazine


Principal Aquifer
Atrazine in urban land-use study wells
Columbia Plateau basin fill–basalt rock (NA)
Snake River Plain basin fill–basalt rock (NA)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (50)
Castle Hayne (NA)
Upper Floridan (25)
Piedmont and Blue Ridge carbonate (NA)
Valley and Ridge carbonate (20)
Cambrian-Ordovician (NA)
Denver Basin (20)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (NA)
Mississippi embayment (9)
Northern Atlantic Coastal Plain (93)
Texas coastal uplands (NA)
Glacial–East (152)
Glacial–Central (128)
Glacial–West Central (174)
Glacial–West (NA)
Basin and Range basin fill (114)
California Coastal Basin (26)
Central Valley (26)
Rio Grande (43)
Alluvial–Denver Basin (39)
Alluvial–Pleistocene terrace deposits (27)
High Plains (30)
Mississippi River Valley alluvial (NA)
Surficial (28)
MCL=3 µg/L
0.001
0.01
0.1
1
10
Concentration, in micrograms per liter

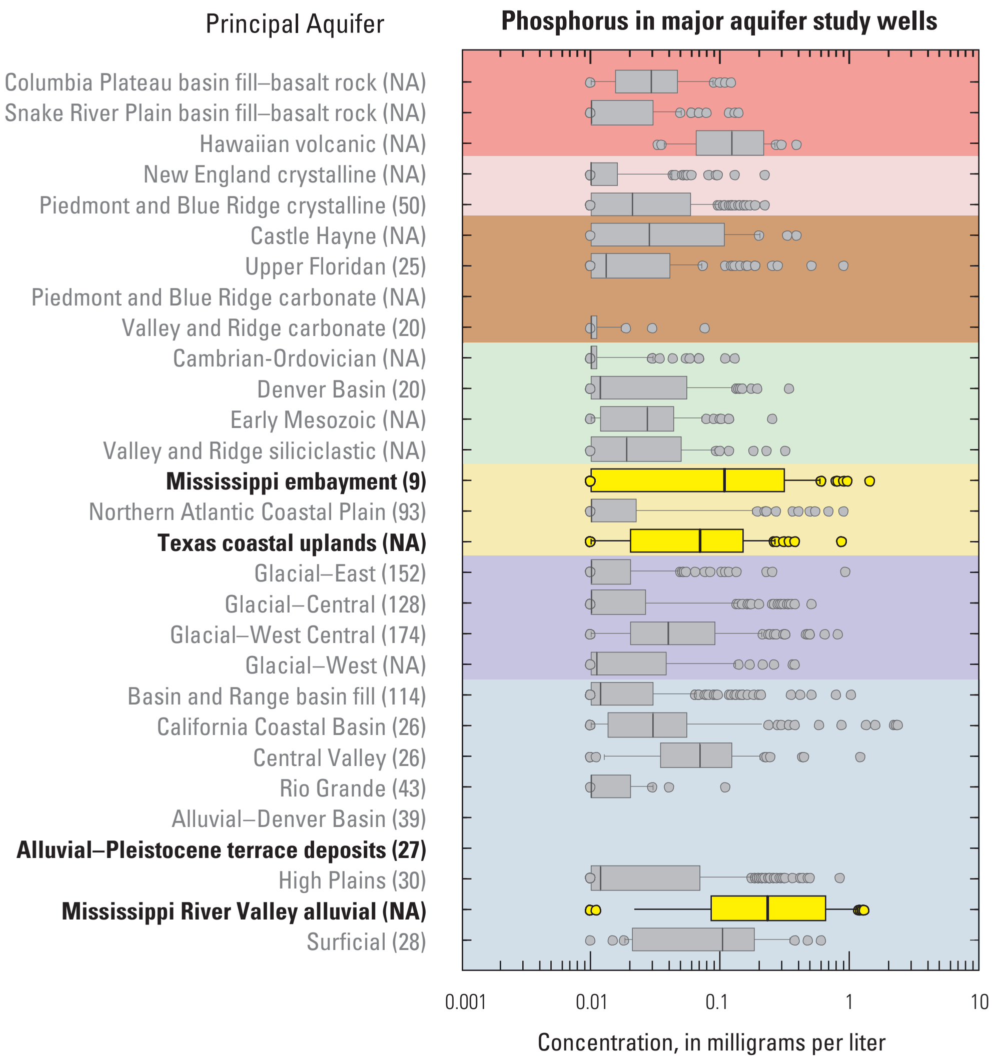
Manganese


Principal Aquifer
Manganese in major aquifer study wells
Columbia Plateau basin fill–basalt rock (43)
Snake River Plain basin fill–basalt rock (98)
Hawaiian volcanic (30)
New England crystalline (117)
Piedmont and Blue Ridge crystalline (170)
Castle Hayne (30)
Upper Floridan (154)
Piedmont and Blue Ridge carbonate (NA)
Valley and Ridge carbonate (30)
Cambrian-Ordovician (139)
Denver Basin (79)
Early Mesozoic (73)
Valley and Ridge siliciclastic (59)
Mississippi embayment (74)
Northern Atlantic Coastal Plain (119)
Texas coastal uplands (66)
Glacial–East (139)
Glacial–Central (199)
Glacial–West Central (161)
Glacial–West (64)
Basin and Range basin fill (279)
California Coastal Basin (133)
Central Valley (63)
Rio Grande (30)
Alluvial–Denver Basin (NA)
Alluvial–Pleistocene terrace deposits (27)
High Plains (338)
Mississippi River Valley alluvial (NA)
Surficial 30)
SMCL=50 µg/L
0.1
1
10
100
1,000
10,000
100,000
Concentration, in micrograms per liter

Nitrate plus nitrite (nitrate)



Phosphorus



Principal Aquifer
Phosphorus in major aquifer study wells
Columbia Plateau basin fill–basalt rock (NA)
Snake River Plain basin fill–basalt rock (NA)
Hawaiian volcanic (NA)
New England crystalline (NA)
Piedmont and Blue Ridge crystalline (50)
Castle Hayne (NA)
Upper Floridan (25)
Piedmont and Blue Ridge carbonate (NA)
Valley and Ridge carbonate (20)
Cambrian-Ordovician (NA)
Denver Basin (20)
Early Mesozoic (NA)
Valley and Ridge siliciclastic (NA)
Mississippi embayment (9)
Northern Atlantic Coastal Plain (93)
Texas coastal uplands (NA)
Glacial–East (152)
Glacial–Central (128)
Glacial–West Central (174)
Glacial–West (NA)
Basin and Range basin fill (114)
California Coastal Basin (26)
Central Valley (26)
Rio Grande (43)
Alluvial–Denver Basin (39)
Alluvial–Pleistocene terrace deposits (27)
High Plains (30)
Mississippi River Valley alluvial (NA)
Surficial (28)
0.001
0.01
0.1
1
10
Concentration, in milligrams per liter

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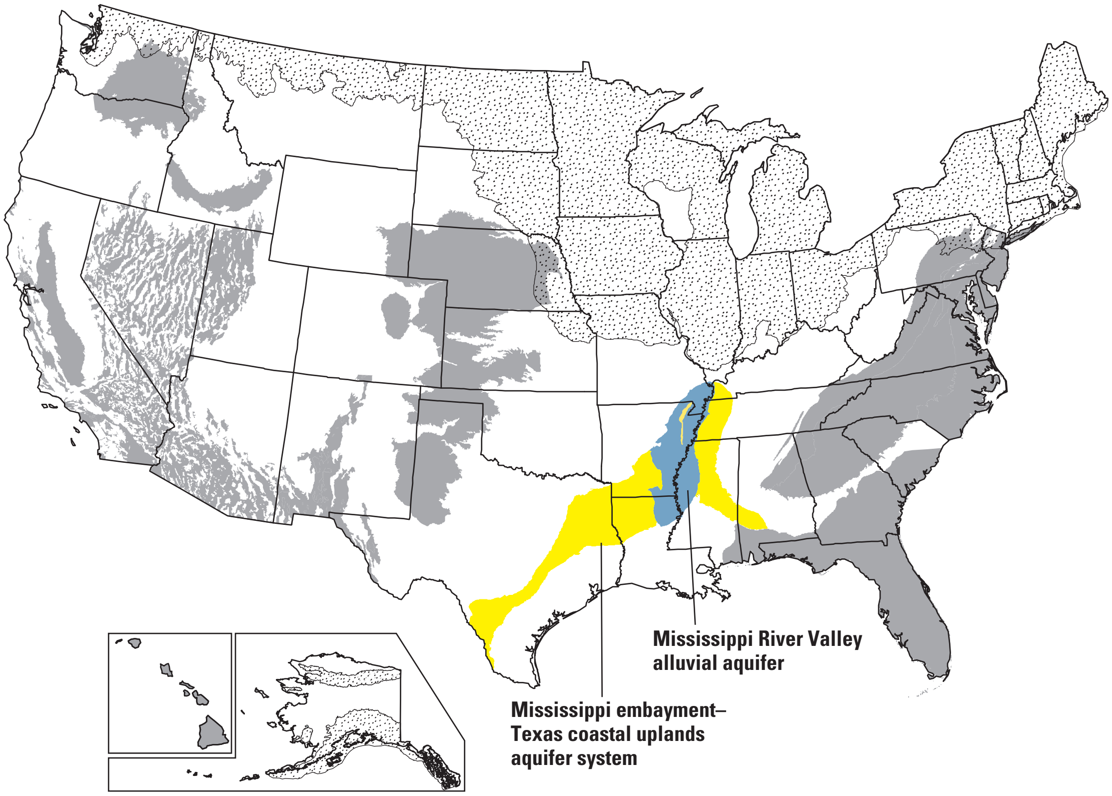

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